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AFRL 711 HPW/OMCA memo dtd 26 Jul 2011

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AFRL-RH-WP-TR-2008-0095

CV-22 Human Vibration Evaluation

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April 2008
Interim Report for April 2007 to October 2007

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE (DD-MMM-YYYY) Apr 2008	**2. REPORT TYPE** Interim Report	**3. DATES COVERED (From – To)** April 2007 – October 2007

4. TITLE AND SUBTITLE
CV-22 Human Vibration Evaluation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
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*David R. Bowden

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
02

5f. WORKUNIT NUMBER
71840223

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

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Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

10. SPONSOR / MONITOR'S ACRONYM
AFRL/RHPA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RH-WP-TR-2008-0095

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution authorized to U.S. Government Agencies only; Test and Evaluation; April 2008. Refer other requests for this document to AFRL/RHPA, 2800 Q Street, WPAFB OH 45433-7947

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The purpose of this study was to characterize and assess human vibration exposure onboard the CV-22 Osprey. Triaxial acceleration data were collected at the pilot station and flight engineer station in the cockpit, and at the crew chief station located at the front right side of the cabin. At all three stations, measurements were made at the seat base and at the interfaces between the occupant and seat pan and occupant and seat back for selected flight conditions. Acceleration data were also collected at the pilot helmet. The engineering data were used to evaluate characteristics of the frequency spectra as well as the direction, measurement site, and location (station) dependence of the vibration levels. Special conditions, including the disabling of the Active Vibration Suppression System (AVSS) and a light vs heavy aircraft, were also evaluated. The accelerations at the seat pan and seat back were weighted in accordance with ISO 2631-1: 1997 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements (1) are used to assess the comfort and health risk of the exposures. A rating scale of satisfactory, marginal, and unsatisfactory was established for comfort and health risk based on the standard guidelines. The overall rating for comfort was marginal. The overall rating for health risk was marginal based on data collected at the pilot station with an exposure time greater than 3 hours but less than 10 hours in duration.

15. SUBJECT TERMS
Human vibration, CV-22 Osprey, human factors, human vibration assessment, operational vibration

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON:**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Suzanne D. Smith
U	U	U	SAR	66	**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

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PREFACE

This report describes the study conducted by the Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (AFRL/RHPA), Wright-Patterson AFB, OH, to characterize the human vibration environment and assess the associated comfort/annoyance and potential health risk during mission-representative flight conditions onboard the US Air Force CV-22 Osprey. The study was conducted at the request of the Air Force Flight Test Center, 412th Test Wing, at Edwards AFB, CA to meet the objectives of the Aircrew Systems Integration Test Plan for the CV-22 Engineering Manufacturing Development (EMD) Program, Crew Interface Vehicle Test Plan. The point-of-contact was Lirio N. Aviles, 412 TW/ENFH. The study was conducted at Hurburt Field, FL onboard the CV-22 Osprey Tail Number 50028 with flight support from the 413FLTS/DOR. The Principal Investigator for the vibration study was Dr. Suzanne D. Smith (AFRL/RHPA). The Test Conductor was Major Amy Cox, 413FLTS/DOR. The pilot was Lt Col Thomas E. Goodnough, 413FLTS/CC. Three occupant locations were targeted for the vibration assessment: the pilot and flight engineer stations located in the cockpit, and the crew chief station located in the cabin. Triaxial accelerations were collected at the seat base and at the interfaces between the occupant and seating system in accordance with ISO 2631-1: 1997 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. Data were collected during two sorties on 14 June 2007 for specified flight conditions. This report summarizes the characteristics of the vibration at each of the locations based on the actual measured accelerations and the accelerations weighted in accordance with ISO 2631-1: 1997. The weighted values reflect the human perception of the vibration. The weighted values were specifically used to assess the comfort reaction and health risk during operation of the aircraft in accordance with the ISO standard. This report provides recommendations based on the results of this study.

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SUMMARY

The purpose of this study was to characterize and assess human vibration exposure onboard the CV-22 Osprey. Triaxial acceleration data were collected at the pilot station and flight engineer station in the cockpit, and at the crew chief station located at the front right side of the cabin. At all three stations, measurements were made at the seat base and at the interfaces between the occupant and seat pan and occupant and seat back for selected flight conditions. Acceleration data were also collected at the pilot helmet. The engineering data were used to evaluate characteristics of the frequency spectra as well as the direction, measurement site, and location (station) dependence of the vibration levels. Special conditions, including the disabling of the Active Vibration Suppression System (AVSS) and a light vs heavy aircraft, were also evaluated. The accelerations at the seat pan and seat back were weighted in accordance with ISO 2631-1: 1997 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements (1), and used to assess the comfort and health risk of the exposures. A rating scale of Satisfactory, Marginal, and Unsatisfactory was established for comfort and health risk based on the standard guidelines. Data were collected on one day during two sorties. At all three stations, the majority of flight test conditions were estimated to be "fairly uncomfortable" according to the ISO 2631-1: 1997 guidelines, which are independent of time. Based on this assessment, the overall rating for comfort during flight operations aboard the CV-22 was marginal. For health risk, cruise in both airplane mode (Cruise Apln Mode) and conversion mode (Cruise Conv Mode) were used for the assessment, assuming these conditions represented the major portion of a mission. Since the Health Guidance Caution Zones (ISO 2631-1: 1997) are time-dependent, the allowable exposure durations within the zones were determined for each station. The highest weighted acceleration at the seat pan occurred in the vertical (Z) direction. During Cruise Apln Mode, low health risk was associated with mean allowable daily exposure durations that fell below 2.8 hours at the pilot station (PI), below 6.9 hours at the flight engineer station (FE), and below 16.8 hours at the crew chief station (CC). During Cruise Conv Mode, low health risk was associated with mean allowable daily exposure durations that fell below 3.4 hours at the pilot station, below 5.5 hours at the

flight engineer station, and below 8.3 hours at the crew chief station. These exposures were rated as Satisfactory. During Cruise Apln Mode, likely health risks were associated with mean allowable daily exposure durations that fell above 11.3 hours at the PI, and above 24 hours at the FE and CC. During Cruise Conv Mode, likely health risks were associated with mean allowable daily exposure durations that fell above 13.6 hours at the pilot station, 21.8 hours at the flight engineer station, and 24 hours at the crew chief station. These daily exposures were considered Unsatisfactory. Those daily exposure durations falling between the low health risk and likely health risk boundaries were considered a potential threat to health risk and rated as Marginal. It was assumed that the CV-22 missions would normally be greater than 3 hours but less than 10 hours in length, for an overall health risk rating of Marginal.

INTRODUCTION

Figure 1. CV-22 Osprey

The CV-22 is the AF variant of the V-22 Osprey (Figure 1). Its mission is to provide long-range, Vertical/Short Takeoff and Landing (V/STOL) insert, extract, and re-supply capability for the Air Force Special Operations Force (SOF). The tilt rotor design of the Osprey combines the vertical flight capability of a helicopter with the speed and range of a turboprop propeller aircraft. The Aircrew Systems Integration Test Plan for the CV-22 Engineering Manufacturing Development (EMD) Program, Crew Interface Vehicle Test Plan defines the human factors engineering requirement for the evaluation and assessment of the operational human vibration exposure expected during normal mission scenarios onboard the CV-22 aircraft. The objective of this study was to characterize the human vibration environment and assess the associated comfort/annoyance and potential health risk during mission-representative flight conditions. These data can be used to recommend and/or develop mitigation processes and strategies. Evaluation criteria were developed to provide specific guidelines on occupant exposure during CV-22 flight operations.

METHODS AND MATERIALS

Aircraft, Measurement Locations, and Test Personnel

This study was conducted on the CV-22 Osprey Tail Number 50028 at Hurlburt Field, Florida. Three occupant locations were evaluated in the aircraft. In the cockpit or flight deck, vibration was evaluated at the pilot station (PI) located on the right side of the aircraft, and at the flight engineer station (FE), where the seating system was attached to the cockpit door. In the cabin area, vibration was evaluated at the crew chief station (CC) located on the right side of the aircraft next to the cabin door. The pilot was a male weighing approximately 102 kg (225 lbs) including gear, with a height of approximately 185 cm (73 in). The individual occupying the flight engineer station was a female weighing approximately 86 kg (190 lbs) including gear, with a height of approximately 140 cm (55 in). This individual also acted as the test conductor. The individual located at the crew chief station in the cabin area was a female weighing approximately 70 kg (155 lbs) including gear, with a height of approximately 170 cm (67 in).

Equipment and Instrumentation

The Remote Vibration Environment Recorder (REVER), developed by AFRL/RHPA, was used to collect human-related vibration data during flight operations on board the CV-22 (Figure 2). Three REVER systems were used; each system was dedicated to a particular occupant station in the aircraft. Two of the 16-channel data acquisition units (DAUs) measured approximately 16.5 by 10 by 4 centimeters. The third DAU measured approximately 9.5 by 7 by 2.8 centimeters. The DAU enclosure was fabricated using Delrin and T6-6061 aluminum and provided electromagnetic interference (EMI) shielding. Two types of battery packs were available for use depending on the flight time. The first measured approximately 5 by 9 by 3

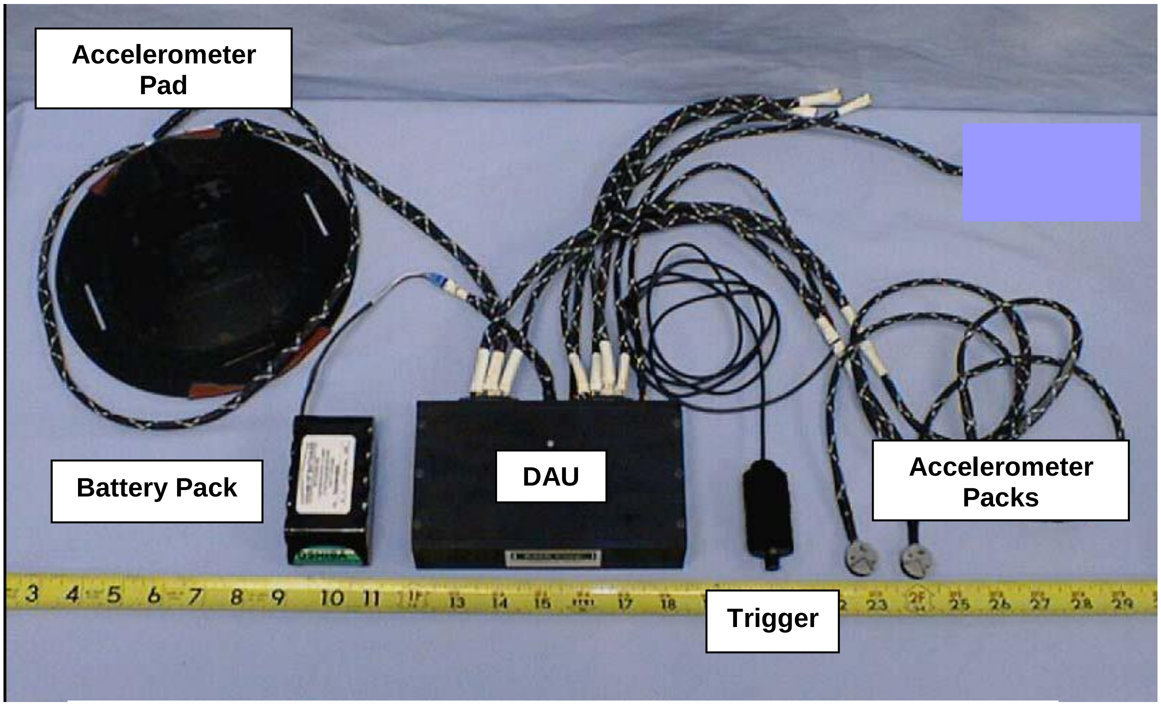

Figure 2. Remote Vibration Environment Recorder (REVER) used to collect acceleration data in aircraft for human vibration analysis.

centimeters. The battery operated for approximately 2 – 2.5 hours. The second measured approximately 7 by 9 by 3 centimeters. This battery operated for approximately 3.5 - 4 hours. The total system weighed 1.4 to 1.6 kilograms (3.0 to 3.5 pounds) depending on the DAU and battery selection.

At each occupant station, a triaxial accelerometer pack was used to measure the input acceleration in the fore-and-aft (X), lateral (Y), and vertical (Z) directions (Figure 2). The pack included three orthogonally-arranged miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) embedded in a Delrin® cylinder. Double-sided mounting tape was used to secure the pack to the appropriate location. The pack measured 1.9 centimeters in diameter and 0.86 centimeters in thickness and weighed approximately 5 grams (25 grams with connecting cable).

Accelerometer pads were used to measure the vibration transmitted to the occupant via the seat pan and seat back 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 (1). The pad was a flat rubber disk approximately 20 centimeters in diameter and weighing 355 grams (with connecting cable) (Figure 2). Embedded in the disk was a triaxial accelerometer pack. Double-sided adhesive tape was used to secure the pads. A triggering device, measuring 7.6 centimeters in length and 2.2 centimeters in diameter with a weight of 20 grams, was used by each occupant to initiate the data collection (Figure 2). The triggering device could be attached to the leg using Velcro®.

Figure 3. AIRSAVE vest with vibration equipment located in outside pocket

The smaller DAU and batteries were carried in the outside vest pocket of a Navy AIRSAVE survival vest (Figure 3) worn by the pilot. At the pilot station (PI), the accelerometer pack was secured to the rigid seat frame at the back of the seat. At the flight engineer station (FE), the DAU, batteries, and accelerometer pack were attached to the cockpit door behind the seat pan (Figure 4a). In the cabin at the crew chief station (CC), the DAU, batteries, and accelerometer pack were mounted to the floor beneath the seat pan (Figure 4b). For all three stations, the location of the input accelerometer pack will be referred to as the seat base. At the PI, the accelerometer pads were secured onto the top of the seat pan and seat back cushions (Figure 5a). At the FE and CC, the pads were secured onto the top of the cloth seat pan and onto the metal frame behind the cloth seat back (Figures 5b-d).

A helmet bar was mounted to the top of the pilot's helmet for estimating the head translational and rotational accelerations (Figure 6a, 6b). The helmet bar consists of six

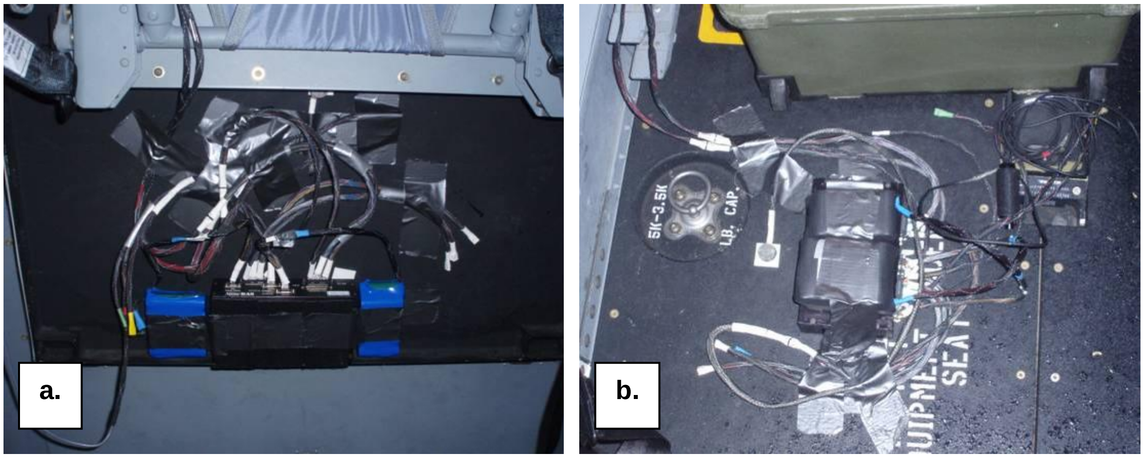

Figure 4. DAU, batteries, and accelereometer pack attachments a. Cockpit door at FE, b. Floor at CC

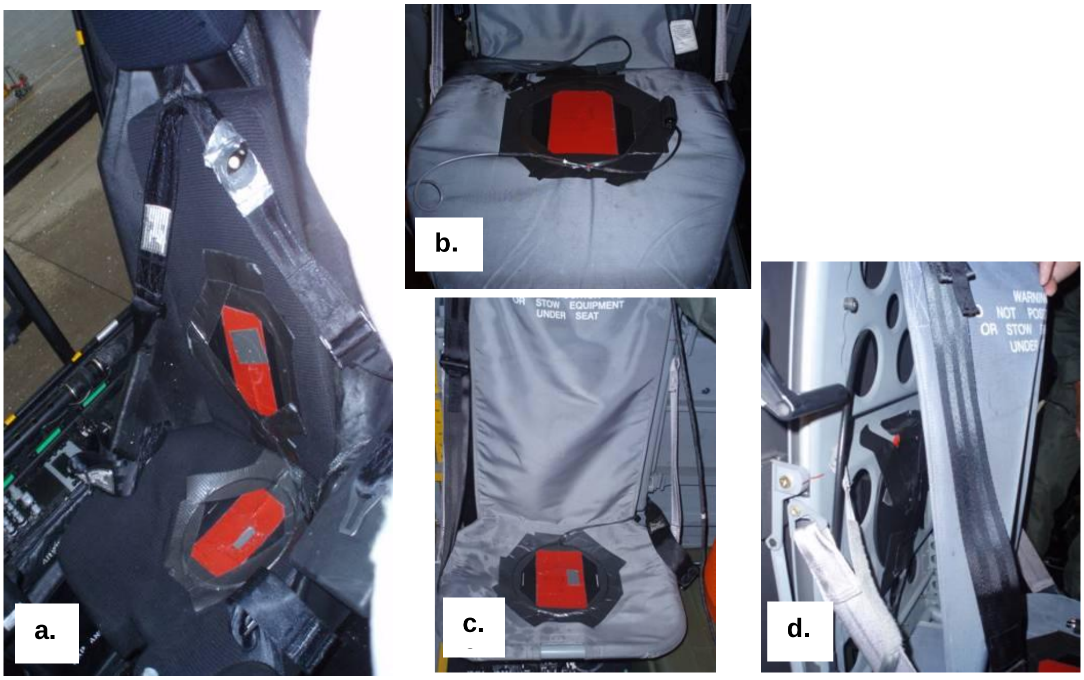

Figure 5. Acceleration pads attached to seats. a. PI seat pan and seat back, b. FE seat pan, c. CC seat pan, d. FE and CC seat back

miniature accelerometers (Entran EGAX-25) strategically arranged for calculating helmet rotation in roll, pitch, and yaw (Figure 6c). The helmet bar was secured to the helmet using double-sided mounting tape and duct tape.

For the pilot, the seat accelerometer cables were connected to the DAU at the lower left side of the survival vest (Figure 3). The cables ran beneath the lap belt to ensure no

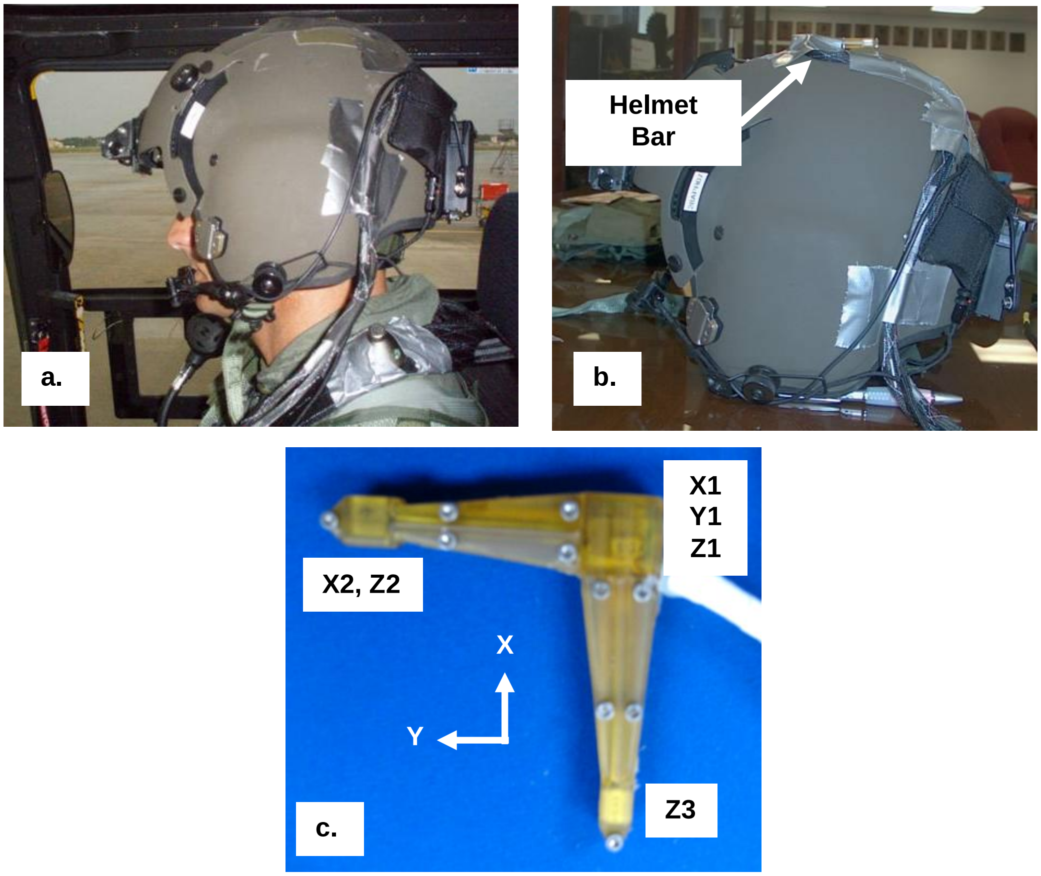

Figure 6. a. Pilot wearing instrumented helmet, b. Helmet bar secured to top of helmet, c. Helmet Bar

interference with the safety features of the aircraft. The cables from the helmet were secured to the helmet and ran over the left shoulder to the DAU connection at the front of the vest. All cable connections between the seat and helmet accelerometers and the DAU were made via break-away connectors that require less than 21.8 N (4.9 pounds) to separate. A flight clearance for the REVER systems was granted by NAVAIR.

Flight Test Conditions

Acceleration data were collected at the three occupant locations for the flight test conditions given in Appendix A, Table A-1. The data included in this report were collected during two sorties on 14 June 2007. The data collected for the Cruise Conv

Mode at 3K ft, IGE Hover at 103.8% RPM, and the Conversions at 3K ft allowed for the additional condition of aircraft weight (Heavy vs Light).

Data Collection and Processing Methods

The test conductor (individual occupying the flight engineer station or FE) prompted the pilot (PI) and individual at the crew chief station (CC) to trigger the DAU for data collection (via headset) once the pilot indicated that the aircraft was on the targeted flight test condition. The data were automatically collected for 20 seconds, low pass filtered at 250 Hz (anti-aliasing) and digitized at 1024 samples per second. The digitized data were downloaded onto a computer after each sortie. Each 20-segment data segment represented one test record associated with a specific flight test condition listed in Table A-1.

The acceleration time histories collected at each location in each direction and associated with a data segment listed in Table A-1 were processed using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) to estimate the constant bandwidth spectral content. Using Welch's method (2), each 20-second time history was divided into 2-second sub-segments with a 50% overlap. A Hamming window was applied to each sub-segment and the resultant power spectral densities were averaged for the 20-second period. The root-mean-square (rms) acceleration, a_{rms}, was calculated from the power spectral densities at 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 by Couvreur (3) for MATLAB®. The program generates the rms acceleration level in each one-third octave band and is reported at the center frequency of the band.

With reference to Figure 6c, the helmet roll rotation acceleration was estimated as the difference between the acceleration time histories measured at Z1 and Z2 divided by the moment arm (0.0508 m); pitch acceleration was estimated as the difference between the acceleration time histories measured at Z1 and Z3 divided by the moment arm (0.0508 m); and yaw acceleration was estimated as the difference between the time histories measured at X1 and X2 divided by the moment arm (0.0508 m). The rotation acceleration constant bandwidth spectra were estimated as described above.

The overall rms acceleration level between 1 and 80 Hz was calculated at each station at the seat base, seat pan, and seat back in each direction (X, Y, and Z) as

$$a = \left[\sum_i a_i^2 \right]^{1/2} \qquad 1$$

where a_i 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 overall translational and rotational helmet accelerations were also calculated as described above.

The assessment of comfort/annoyance and health risk followed the guidelines in ISO 2631-1: 1997 standard (1). The standard requires the application of frequency weightings and multiplying factors to the acceleration data that are based on human sensitivity to the location, frequency, and direction of the vibration. Table 1 lists the frequency weightings and multiplying factors used to assess the comfort reaction and health risk. Figure 7 illustrates the frequency weightings W_d, W_k, and W_c.

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

	HEALTH RISK Seat Pan		COMFORT REACTION Seat Pan		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	$k = 0.4$

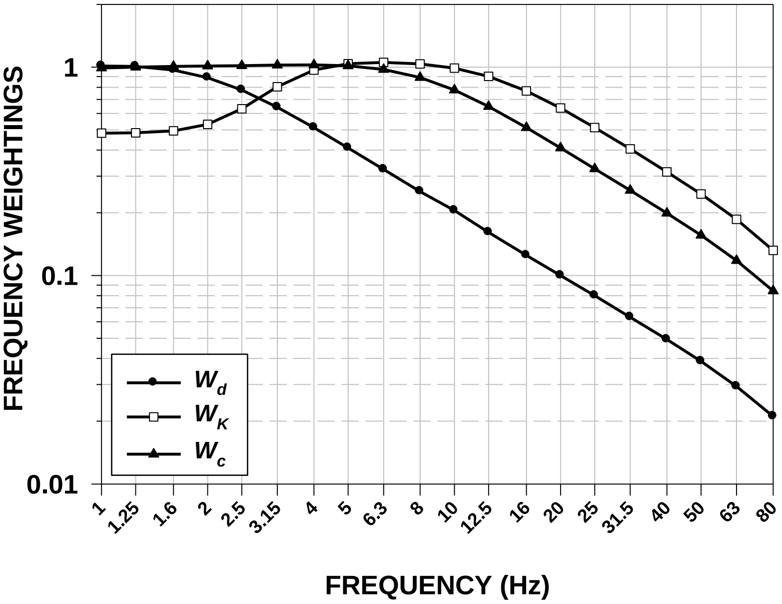

Figure 7. Frequency Weightings Wd, Wk, and Wc (ISO 2631-1: 1997 (1))

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

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

where *j* represents the particular frequency weighting (*d*, *k*, or *c*) depending on the location and direction (Table 1), *i* represents the *ith* frequency component, and a_{rmsi} is the measured one-third octave acceleration level at center frequency *i*. For assessing comfort, 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 factor to a_w in the respective direction (Table 1):

$$pVTV = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \; . \qquad 3$$

The overall *VTV* was calculated as the vector sum of the seat pan and seat back *pVTV*. The overall *VTV* was 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, 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 1. The weighted data were compared to the ISO Health Guidance Caution Zones (ISO 2631-1: 1997, Annex B (1)). The ISO 2631-1: 1997 (1) also states that the vector sum of the weighted accelerations can be used when vibration in two or more axes are similar. For weighted accelerations falling below the lower boundary of the ISO Health Guidance Caution Zones for the expected duration, health effects are unlikely. For those levels falling between the two boundaries, caution is given with respect to health risk. For those levels falling above the upper boundary, health risks are likely for repeated occupational exposures.

Evaluation Criteria

In accordance with the Aircrew Systems Integration Test Plan for the CV-22 Engineering Manufacturing Development (EMD) Program, comfort and health risk evaluation criteria for human vibration aboard the CV-22 were established. The exposures were assigned ratings of Satisfactory, Marginal, or Unsatisfactory based on the guidelines give in ISO 2631-1: 1997 (1). The Evaluation Criteria are listed in Table 2.

Table 2: Evaluation Criteria

Satisfactory	The weighted seat pan acceleration in any direction falls below the lower boundary of the ISO Health Guidance Caution Zones based on the expected mission duration.	Health Risk (ISO 2631-1: 1997, Annex B, Figure B.1, Eq. B.1)
	The overall Vibration Total Value (VTV) is equal to or less than the vibration level associated with a comfort reaction of “fairly uncomfortable”.	Comfort $VTV \leq 0.5$ (ISO 2631-1: 1997, Annex C, Section C.2.3)
Marginal	The weighted seat pan acceleration in any direction falls within the upper and lower boundaries of the ISO Health Guidance Caution Zones based on the expected mission duration.	Health Risk (ISO 2631-1: 1997, Annex B, Figure B.1, Eq. B.1)
	The overall VTV falls within the vibration levels associated with a comfort reaction of “fairly uncomfortable”.	Comfort $0.5 < VTV \leq 0.1$ ms^{-2} rms (ISO 2631-1: 1997, Annex C, Section C.2.3)
Unsatisfactory	The weighted seat pan acceleration in any direction exceeds the upper boundary of the ISO Health Guidance Caution Zone based on the expected mission duration.	Health Risk (ISO 2631-1: 1997, Annex B, Figure B.1, Eq. B.1)
	The overall VTV is greater than the vibration level associated with the “fairly uncomfortable” comfort reaction.	Comfort $VTV > 1.0$ ms^{-2} rms (ISO 2631-1: 1997, Annex C, Section C.2.3)

RESULTS

Characteristics of the CV-22 Frequency Spectra

Appendix B includes the tables and figures associated with the results of this study. Propeller and rotary-wing aircraft exhibit relatively distinct vibration frequency components associated with the rotor speed or propeller rotation frequency (PRF) and number of propeller blades. For those flight test conditions depicted in Table A-1 that were not transitory in nature (i.e. flown at constant rotor speed or PRF), three operating speeds or PRFs were common. At 100%, the rotor speed was approximately 397 revolutions per minute (RPM) or approximately 6.6 Hz. Table A-1 lists the RPM associated with each flight test condition. Table A-2 lists the estimated rotor speed or the one per revolution (1P) frequency defined for the three operating speeds (also the PRF).

The three per revolution (3P) frequency was associated with the blade passage frequency (BPF) and was defined as the number of blades (three) times the PRF. Also listed are the multiple frequency components associated with the PRF. Figure B-1 illustrates the constant bandwidth acceleration spectra at the seat pan for selected flight conditions associated with the three operating speeds at the PI (a), the FE (b), and the CC (c). Given the processing technique described in the **METHODS AND MATERIALS**, the spectral resolution of the frequency components was 0.5 Hz. The figure shows the differences in the spectral components depending on the operating speed of the flight condition, the location of the crew member, and the direction of the vibration.

During Cruise Apln Mode, both the PI and FE, located in the cockpit of the aircraft, showed a prevalence of vibration occurring at multiples of the PRF (3P, 6P, 9P, 12P, Figures B-1a and B-1b) but particularly at the BPF (16.5 Hz) in the vertical (Z) direction. Low vibration levels occurred in the lateral (Y) direction at the PI and FE during Cruise Apln Mode. In contrast, the CC showed a prevalence of higher frequency vibration during Cruise Apln Mode (3P, 6P, 9P, 12P, Figure B-1c) in all three directions.

During Cruise Conv Mode, distinct peaks were observed in the fore-and-aft (X) direction at the stations located in the cockpit (PI and FE) and were associated with the expected spectral components at 1P (PRF), 3P (BPF), and 6P (2 X BPF). There was notable lateral (Y) and vertical (Z) vibration in a broad band between about 6.5 Hz and 20 Hz, with a relatively distinct peak at 3P around 20 Hz, particularly in the vertical (Z) direction. The CC showed more distinct peaks at the seat pan in all three directions during Cruise Conv Mode, particularly at 3P or the BPF (20 Hz) (as opposed to the broad frequency band noted at the PI and FE). Of particular interest was the small seat pan peak occurring at 4 Hz in the Y direction at the PI and FE, with a barely noticeable peak at 6.5 Hz (1P). This 4-Hz peak was also observed in the X direction at the CC, along with the 6.5 Hz (1P) peak. It was not clear what caused the small 4 Hz peak to consistently occur, but it was also observed at the cockpit seat bases and most likely related to another structural resonance in the aircraft.

Both the PI and FE in the cockpit showed relatively low vibration during IGE Hover compared to the cruise conditions. For the CC located in the cabin, distinct acceleration peaks were observed at the PRF in the X and Z axes (20.5 Hz). Multiple measurements were made at the flight conditions depicted in Figure B-1 (Table A-1). A comparison showed high similarity in the spectral components. Differences due to the conditions of the FE door position, cabin door position, and Active Vibration Suppression System (AVSS) will be discussed later in this report.

Overall Rms Acceleration Levels

Figures B-2a-c illustrate the overall rms acceleration levels associated with the major flight conditions at each measurement site (seat base, seat pan, and seat back) and in each direction at the PI, FE, and CC, respectively. For those conditions where multiple points were collected, the mean value ± 1 standard deviation is shown. These mean values also include the conditions of altitude, speed setting, FE upper door position, cabin door position, and AVSS setting. It is noted that the high levels of seat back vibration observed at the FE are most likely due to posture. The individual occupying this station was the test conductor and was documenting the test activity during the flight. As a result, the individual reported that she may not have been seated with her back in contact with the seat back for many of the test points. The figures emphasize that vibration aboard the CV-22 occurs in all three directions (X, Y, and Z). In general, lower vibration, primarily below 1.0 ms^{-2} rms, was observed at the FE seat pan as compared to the other two stations. The seat back data could not be compared due to the influence of posture at the FE. Certain flight conditions produce higher vibration depending on the location, measurement site, and direction. For example, climb in conversion mode (Climb Conv) resulted in relatively high levels of seat base and seat back vibration in the vertical (Z) direction at the PI and CC (Figures B-2a and B-2c). This tendency was also observed at the PI seat pan. Descent also produced relatively high levels of vibration, especially at the CC seat pan and seat back in all three directions (Figure B-2c).

It was assumed that, for long duration missions, a high percentage of time would be spent in the cruise conditions. At the cockpit stations (PI and FE), the general trend was for higher horizontal (X, Y) seat vibration (seat pan and seat back, excluding the FE seat back) during Cruise Conv Mode as compared to Cruise Apln Mode (Figures B-2a and B-2b). In contrast, the cabin station (CC) showed substantially higher horizontal (X and Y) seat vibration and vertical (Z) seat pan vibration during Cruise Apln Mode (Figure B-2c). Figure B-1c suggests that the higher overall seat pan levels at the CC during Cruise Alpn Mode may be due to the presence of higher frequency components.

Specific Flight Test Conditions

Conversion

The conversion and re-conversion test conditions were associated with the transition of the aircraft between the conversion mode and airplane mode. The spectral characteristics of the vibration changed during this period due to changes in the rotor speed or propeller rotation frequency (PRF) as shown in Tables A-1 and A-2. Figure B-3 shows a waterfall plot of the spectral components for four test points that were collected at the pilot seat pan as the aircraft transitioned from the conversion mode to the airplane mode. The shift in the BPF from approximately 20 Hz to 17 Hz (3P in Table A-2) and the shift at 2 X BPF from approximately 40 Hz to 33 Hz (6P in Table A-2) can be seen, particularly for Seat Pan X and Seat Pan Z (marked with arrows).

Altitude

The effects of altitude were evaluated during Cruise Apln Mode and Cruise Conv Mode. There appeared to be a tendency for a reduction in the overall rms acceleration levels with a decrease in altitude depending on the location (station), measurement site, and direction. The altitude effect was more notable during Cruise Conv Mode. Figure B-4 illustrates the overall acceleration levels at the PI and CC during Cruise Conv Mode at 5K and 3K ft MSL. The results at the FE were similar to those observed at the PI. The figure shows that the most notable differences occurred in the X direction for stations located in the cockpit, and in the Z direction for the CC in the cabin area.

Engine RPM

Approach to IGE Hover, IGE Hover, Approach to OGE Hover, and OGE Hover were collected during Flight B with the engine speed at 103.5% and 100%. The vibration data at all three stations, all measurement sites, and in all three directions showed substantial variability during Flight B for the conditions where multiple points were collected. This may have been due to less than ideal weather conditions. Given the large variability, the CC did show substantially higher vibration in the vertical (Z) direction at the seat base, seat pan, and seat back at 100% RPM as compared to 103.5% RPM during both IGE and OGE Hover. Figure B-5 includes the mean overall seat pan acceleration levels at the CC for the IGE Hover test conditions at the two engine settings at the CC. For the single test points collected during the approaches, it was very difficult to determine any trends in the data. There appeared to be no substantial effect of the engine speed on the measured vibration levels during the Approach to IGE Hover and Approach to OGE Hover.

Aircraft Weight

Selected flight test conditions listed in Table A-1 were repeated to compare the vibration levels associated with a heavy and light aircraft (based on fuel weight). Cruise Conv Mode at 3000 ft was flown at the beginning and towards the end of Flight A. Conversion (Conv to Apln) and IGE Hover were flown during Flights A and B. During Conversion, there were relatively large variations in the overall acceleration levels and it was difficult to observe any clear trends due to the weight of the aircraft. During Cruise Conv Mode, both stations in the cockpit (PI and FE) tended to show lower vibration levels in the lateral (Y) direction in the lighter aircraft at all three measurement sites, with the pilot also showing this tendency in the vertical (Z) direction. The results at the CC for this flight condition were variable. The most consistent effect of weight was observed during

IGE Hover. In contrast to the tendencies observed during Cruise Conversion Mode, the PI and FE in the cockpit showed higher vibration in the lateral (Y) and vertical (Z) directions in the lighter aircraft at most measurement sites during IGE Hover, although the changes were small. Substantially higher vibration was observed at the CC in the fore-and-aft (X) and vertical (Z) directions at all three measurement sites in the lighter aircraft during IGE Hover. The effects of weight on vibration levels measured at the CC seat pan are depicted in Figure B-6.

Other Flight Conditions

Other flight conditions included vibration measurements with the FE upper door opened, the cabin door opened, and the Active Vibration Suppression System (AVSS) disabled or turned off (note in Table A-1). Given the variability identified for those conditions where multiple points were collected, there appeared to be no substantial or consistent effects of the FE upper door or cabin door conditions. There also appeared to be no substantial or consistent effects of the AVSS setting. Figure B-5 includes the FE door, cabin door, and AVSS conditions during IGE Hover. There was one instance during IGE Hover where there was a substantial increase in the Seat Back X vibration at the CC with the AVSS disabled or off. It occurred during Flight B with the engines at 100%. Further investigation revealed that this was associated with a substantial increase in the acceleration at the BPF (~41 Hz). Since the seat base and seat pan did not show similar behavior, it was speculated that the result may have been due to posture, i.e., there was not good contact between the body and seat back (similar to the observations at the FE where contact with the seat back was inconsistent).

Pilot Helmet Accelerations

Figure B-7 illustrates an example of the pilot helmet translational and rotational acceleration spectra during Cruise Conversion Mode. A comparison with the seat pan acceleration spectra depicted in Figure B-1a shows that very little vibration was transmitted to the pilot's head above 20 Hz (BPF). The shapes of the helmet vertical (Z) and pitch acceleration spectral plots between 0 and 20 Hz were similar to that observed in the vertical (Z) direction at the seat pan. The shapes of the helmet lateral (Y) and roll acceleration spectral plots were similar to that observed in the lateral (Y) direction of the seat pan, particularly with respect to the 4 Hz peak. Helmet yaw showed a peak at a relatively low frequency (~2 Hz). A review of the acceleration time histories indicated that this motion may have represented voluntary movement of the pilot's head. The helmet rotational accelerations were relatively low. Figure B-8 illustrates the mean overall pilot helmet accelerations ± 1 SD (for multiple test points) in each of the three translational and rotational directions relative to the head coordinate system. The figure shows that the highest helmet translational accelerations occurred in the vertical (Z) direction. Variable results were observed among the helmet rotations. Certain flight conditions did show large variability in the helmet rotations. A closer look at the acceleration time histories provided some explanation for the variability. For example, the large mean and standard deviation noted for the estimated helmet roll and helmet pitch during Cruise Conv Mode appeared to be related to high roll and pitch accelerations for 1 of the 12 data segments used to calculate the mean overall acceleration level. The time histories for the associated segment showed that the Z1 acceleration was uncharacteristically out of phase with the Z2 and Z3 accelerations for approximately 4 out of the 20 seconds, but all three accelerometers showed similar magnitudes in the spectral components (refer to the helmet bar in Figure 6c). However, this produced relatively high values in the calculated helmet roll and pitch accelerations between 6 and 20 Hz. During Approach to OGE, relatively high pitch was observed in 1 of 4 segments. The time histories associated with this segment showed that, while the Z1 and Z2 accelerations remained in phase and with similar magnitudes producing low helmet roll, the Z3 acceleration was out of phase for approximately 5.5 seconds, resulting in the higher pitch calculation. It was assumed that, during most of the data collection activity, all occupants maintained a relatively upright posture with the head looking forward (relative to the seat coordinate system). The two examples given above indicated that there were relatively abrupt and dramatic changes in the rotational acceleration that could not necessarily be accounted for by changes in the head orientation. Factors that may have contributed to the findings include brief periods of contact between the helmet and seat or possible malfunction of helmet bar components that could affect the sensor measurement. It is emphasized that these characteristics were only observed in a limited number of segments. The larger variability observed in helmet yaw for some flight conditions was primarily due to differences between the X1 and X2 accelerations occurring at low frequency. In this case, the result was likely due to voluntary head movements by the pilot.

Weighted Acceleration Levels and Human Perception

Figures B-9a-c illustrate the mean overall weighted accelerations ± 1 SD (for multiple test points) at each of the stations in each of the three directions at the seat pan and seat back. The weighted values can be compared to the unweighted values illustrated in Figures B-2a-c. The figures show that, in accordance with the frequency weightings given in ISO 2631-1: 1997, the crew members would perceive or be the most sensitive to vertical (Z) vibration at the seat pan and fore-and-aft (X) vibration at the seat back (relative to the seated occupant). In addition, the overall weighted accelerations suggested that the occupants would perceive greater vibration at the seat pan as compared to the seat back (excluding the FE seat back data). Figures B-9a and B-9c indicate that the relatively high levels of vertical (Z) seat pan vibration measured during Climb Conv Mode (Figures B-2a and B-2c) would also be perceived as being relatively high compared to other flight conditions at the PI and CC. The high levels of vibration measured at the seat back were greatly reduced once weighted. Of particular interest were the differences in the weighted accelerations for Cruise Conv Mode as compared to Cruise Apln Mode. For the PI and FE, the differences were similar to the unweighted levels; higher horizontal vibration at the seat pan and seat back during Cruise Conv Mode. For the CC, where higher acceleration levels were measured at the seat pan and seat back during Cruise Apln Mode (Figure B-2c), the weighted accelerations suggested that the differences observed in the horizontal (X, Y) directions would not be perceived at the seat back. However, Figure B-9c shows that the weighted seat pan Z accelerations tended to be higher during Cruise Conv Mode as compared to Cruise Apln Mode at the

CC, in contrast to the unweighted measurements. The differences between the weighted and unweighted accelerations can be explained based on the frequency distribution of the exposures. As mentioned previously, the unweighted acceleration spectra in Figure B-2c at the CC during Cruise Apln Mode includes several substantial peaks above 20 Hz as compared to the spectra for Cruise Conv Mode. These higher frequency components become greatly reduced once the ISO frequency weightings have been applied, resulting in lower overall weighted accelerations. According to the ISO 2631-1: 1997, these higher frequency components contribute less to human vibration perception and sensitivity.

The weighted values for specific flight test conditions were compared. For altitude in Cruise Conv Mode, the observable reduction in the X-axis vibration at the cockpit stations (Figure B-4a) was not evident in the weighted seat accelerations. The weighted seat pan Z accelerations observed at the CC were reduced at the lower altitude, similar to the observations in Figure B-4b. For the engine settings during IGE and OGE Hover, Figure B-10 (IGE Hover) shows that the overall weighted seat pan Z vibration was higher at 100% RPM as compared to 103.5% RPM, similar to the trends observed in the unweighted values depicted in Figure B-5 (IGE Hover). The weighted seat back Z accelerations were extremely low. Figure B-11 shows that the overall weighted seat pan Z vibration at the CC was higher with the lighter aircraft during IGE Hover, similar to the trends observed in the unweighted values depicted in Figure B-6. The weighted seat pan X vibration was quite low and did not show the effects of aircraft weight that occurred in the unweighted accelerations (Figure B-6). As with the unweighted accelerations, the condition of the FE upper door (open or close) did not appear to have any effect on the overall weighted seat pan data. Likewise, the condition of the AVSS (on vs off) did not appear to have any effect on the overall weighted seat pan data (Figures B-6, B-11).

Human Vibration Assessment

Comfort

The ISO 2631-1: 1997 provides guidance on estimating the contribution of horizontal seat back vibration to occupant comfort when the vibration at the seat back cannot be measured. For this case, the multiplying factor of 1.4 is applied to the weighted seat pan acceleration levels in the X and Y directions. This is identical to the process used for assessing health risk (Table 1). For the assessment of comfort, the estimated *VTV* was then calculated in accordance with Eq. 3 using the seat pan measurements. This was done due to the questionable seat back measurements obtained at the FE seat back. Figures B-12a-c illustrate the overall *VTV*, calculated as the vector sum of the seat pan and seat back point *VTVs*, and the estimated *VTV*. The mean values ± 1 SD are shown (where appropriate) for the major flight conditions. The distribution of the test points relative to the evaluation criteria (Table 2) are annotated on the plots. Figures B-12a and B-12c show little difference between the overall *VTV* and the estimated *VTV* at the PI and CC. With the exception of Ground Taxi at the CC, the overall *VTVs* were slightly higher as compared to the estimated *VTVs*. This had little effect on the distribution of the ratings. In contrast, Figure B-12b shows a substantial difference between the two calculations for the FE and did show differences in the ratings for the individual test points. Given the uncertainty in the seat back data at the FE, the ratings at the FE were based on the estimated *VTV*, while the PI and CC ratings were based on the overall *VTV*.

The majority of test points for the PI and CC fell between 0.5 and 1.0 ms^{-2} rms, were associated with a comfort reaction of “fairly uncomfortable” (ISO 2631-1: 1997), and were rated Marginal according to the evaluation criteria given in Table 2. The majority of test points for the FE fell below 0.5 ms^{-2} rms, were associated with a comfort reaction of “not uncomfortable” to “a little uncomfortable”, and were rated Satisfactory (based on the estimated *VTV*). Tables B-1, B-2, and B-3 list the mean *VTV*, Comfort Reaction (ISO 2631-1: 1997), and associated rating at the PI, FE, and CC, respectively, for the major flight conditions. Although Table 2 indicates that a rating of Marginal is associated with a comfort reaction of “Fairly Uncomfortable”, there is overlap between the acceleration levels and the comfort reactions. *VTVs* of 0.8 to 1.0 ms^{-2} rms fall in the overlap region between “Fairly Uncomfortable” and “Uncomfortable”. At the PI station, Cruise Conv Mode and Descent produced Overall *VTVs* of 0.81 and 0.88 ms^{-2} rms, respectively, and fell within the overlap region for these two reactions (Table B-1). At the CC station, Ground Taxi, Climb Conv, and Reconversion showed Overall *VTVs* of 0.88, 1.00, and 0.84 ms^{-2} rms, respectively, and fell within this overlap region (Table B-3). The ratings for these exposures are still Marginal in accordance with the Evaluation Criteria given in Table 2. Although not annotated in Tables B-1, B-2, and B-3, *VTV* values between 0.5 and 0.63 ms^{-2} rms fall within an overlap region between “A Little Uncomfortable” and “Fairly Uncomfortable”. The ratings for these exposures are still Marginal in accordance with Table 2.

Health

The ISO Health Guidance Caution Zones (ISO 2631-1: 1997) are defined by the weighted seat pan acceleration level and the expected duration of the exposure. The type and length of the exposure will depend on the particular mission. Since this could vary, the approach was to determine the durations of allowable exposure before reaching the lower and upper boundaries of the ISO Health Guidance Caution Zones. Several of the flight test conditions given in Table A-1 were expected to last less than 10 minutes during a typical mission. As mentioned previously, the cruise flight conditions were expected to occupy a major portion of the operational vibration exposure. The Cruise Apln Mode and Cruise Conv Mode flight conditions were used to estimate the durations of allowable exposure during associated with a typical CV-22 mission based on the evaluation criteria defined in Table 2. Figures B-9a – c show that the highest weighted seat pan accelerations during the two types of cruise conditions occurred in the vertical (Z-axis) direction in the cockpit at the PI station. The lowest weighted seat pan accelerations occurred in the cabin at the CC station. Figures B-13a and B-13b include the ISO Health Guidance Caution Zones with plots of the weighted Z-axis seat pan accelerations for the test points collected at the three stations during the Cruise Apln Mode and Cruise Conv

Mode, respectively. The figures illustrate the approximate time or duration required to reach the boundaries or zones for the measured test points. Figure B-14 illustrates the mean exposure durations allowed during a 24-hour period for each cruise mode based on the weighted seat pan Z accelerations and the evaluation criteria given in Table 2. As shown in Table 2, these durations were defined by the lower and upper boundaries of the ISO Health Guidance Caution Zones. The ISO 2631-1: 1997 does indicate that the vector sum of the weighted seat pan accelerations (VTV) is sometimes used when sufficient vibration occurs in more than one direction. Table B-4 lists the allowable exposure durations based on the weighted seat pan Z accelerations and the vector sum of the weighted seat pan accelerations (VTV) for all measured Cruise Apln Mode test points and includes the mean values ± 1 standard deviation. Table B-5 lists the allowable exposure durations for all measured Cruise Conv Mode test points and includes the mean values ± 1 standard deviation. The allowable exposure durations tended to be lower when based on the VTV. This was particularly evidenced for Cruise Conv Mode (Table B-5). The larger differences seen between the weighted seat pan Z accelerations and the seat pan VTV during Cruise Conv Mode emphasizes the contribution of low frequency horizontal vibration.

DISCUSSION AND CONCLUSIONS

This study characterized the human vibration environment and assessed operational vibration exposure during normal flight mission scenarios onboard the CV-22 Osprey. The study was part of the human factors evaluation of the CV-22 crew vehicle interface. The study evaluated the multi-axis vibration entering the seated occupant located in the cockpit and cabin areas including the pilot, flight engineer, and crew chief stations during selected flight conditions and maneuvers. Specific conditions also evaluated the effects of altitude, cockpit (FE) and cabin door positions, aircraft weight, and the AVSS position (on vs off). The guidelines provided in current human vibration standards were used to measure and assess the effects of the operational exposures on occupant comfort and health risk. Data were analyzed with respect to the measured acceleration spectra to confirm the major frequency components and directions associated with CV-22 flight operations. The overall measured acceleration levels were used to compare the levels of vibration entering the occupant relative to the flight test condition, occupant location, and direction of vibration. The overall weighted accelerations were used to assess the occupant perception of the vibration relative to the flight test condition, occupant location, and direction of vibration.

Both the acceleration spectra and the overall acceleration measurements between 1 and 80 Hz showed that vibration enters the occupant of the CV-22 at both the seat pan and seat back interfaces in all three directions (X, Y, and Z relative to the seated occupant) during CV-22 operations. The frequency components of the vibration are relatively consistent and predictable depending on the occupant location, whether the aircraft is in airplane (Apln) or conversion (Conv) mode, and the particular rotor or propeller rotation speed.

The assessment of the measured vibration and the development of mitigation strategies becomes complicated due to psychophysical effects, or the human perception of the vibration. Humans are sensitive to the frequency, magnitude, and direction of vibration. The frequency weightings and multiplying factors given in ISO 2631-1: 1997 and applied in this study were based on human vibration perception. The significance of this perception is reflected in Figures B-9a – c. Regardless of the similarities between the levels of horizontal and vertical vibration, as well as the similarities in the seat pan and seat back vibration, the weighted accelerations indicated that the occupant would perceive the greatest vibration in the vertical direction at the seat pan, regardless of the location in the aircraft. With reference to Figure 7, it can be seen that, beyond about 2 Hz, the values of the frequency weightings for the horizontal axes becomes increasingly smaller compared to the vertical axis weightings. With respect to the frequency range of concern in the CV-22, the horizontal vibration contributes very little to the occupant's perception of the vibration at the seat pan. The opposite is true at the seat back, where the fore-and-aft vibration has the greatest influence on the occupant's perception of the seat back vibration. These results indicate that any vibration mitigation strategy should concentrate on the vertical vibration at the seat pan and, perhaps, the fore-and-aft vibration at the seat back. In addition, any mitigation strategy should further focus on the weighted acceleration spectra, i.e., those frequency components that have the highest frequency weightings (approaching 1.0) and contribute the most to the overall vibration level. Figure 7 shows that, regardless of the direction, higher frequency components become increasingly less weighted (weightings less than 1.0). As mentioned earlier, when comparing the vibration levels among the various flight conditions, the unweighted and weighted overall accelerations can show different trends, depending on the spectral distribution. It is cautioned that studies continue to evaluate human perception to insure that the frequency weightings are appropriate. However, these studies tend to focus on lower frequency vibration below 10 Hz and not on the higher frequency components associated with rotary-wing and propeller aircraft.

This study also included the estimation of helmet motion. The transmission of vibration to the helmet during CV-22 operations was relatively small and occurred below 20 Hz. This was expected given the transmission characteristics of the body in the vertical direction. If the helmet is in contact with the seat back, then more substantial vibration may be transmitted to the head. The greatest concern with vibration transmission to the helmeted head is with the use of helmet-mounted equipment such as night vision goggles, helmet-mounted displays, and targeting systems. These systems may not function as effectively in a vibration environment where involuntary head motion can occur. The vestibular ocular reflex also becomes less effective when the display is rotating with the head. The result can be visual blurring and difficulty with targeting (4).

A major objective of this study was to assess the effects of operational CV-22 vibration on aircrew comfort and health risk in accordance with the evaluation criteria that was based on the current ISO 2631-1: 1997. The ISO guidelines are based on the weighted acceleration levels. With respect to comfort, the acceleration levels given in ISO 2631-1: 1997, Appendix C are approximate indications of the likely reactions to the magnitudes of overall total values in public transportation. While being independent of time, the durations of these exposures are most likely less than those expected during military operations. However, the perception of military occupants exposed to vibration while performing their duties may not be the same as that of civilian passengers traveling in public transport vehicles. Overall, the CV-22 vibration exposures were considered Marginal with respect to the ISO comfort reactions, falling between 0.5 and 1.0 ms^{-2} rms with an ISO rating of "fairly uncomfortable". These exposures should be viewed with caution, particularly during prolonged exposures, where other factors will also contribute to the assessment of discomfort. These factors include seat design, posture, and other ergonomic issues associated with operating the aircraft, as described below with respect to health risks.

The health risk assessment conducted in this study was based on level flight cruise maneuvers in both the airplane and conversion modes. It is speculated that daily operations of the CV-22 will typically exceed 3 hours in duration which is considered marginal with respect to health risk (based on the limiting exposures during Cruise Apln Mode at the pilot station). Marginal exposures fall between the Health Guidance Caution Zones of the ISO 2631-1: 1997 where caution is given with respect to health risk. It is also speculated that daily operations of the CV-22 will not typically exceed 10 hours in duration. Based on the levels of vibration occurring during cruise, the daily exposures would most likely not reach the unsatisfactory levels.

Historically, the major health risk to rotary-wing pilots has been low back pain or low back injury during prolonged and repeated exposures to operational vibration. Other factors that contribute to these symptoms include sitting in one position with less than optimum posture for long periods of time. There have been increasing anecdotal reports of buttocks and lower extremity numbing during prolonged operations in both rotary- and fixed-wing aircraft where there is little opportunity to change sitting position or posture. The causes and extent of these symptoms among the DoD operational community has not been determined. Therefore, the health risks are unknown. These symptoms could increase discomfort, lead to fatigue, reduce performance, and produce safety hazards. Unfortunately, the current standards do not specifically address fatigue and performance degradations resulting strictly from vibration exposure since they are affected by so many variables.

The weighted accelerations used for the comfort and health risk assessments are based on the vibration entering the seated occupant. These levels can vary depending on the occupant’s anthropometry, posture, and activity at the time of the measurement. Given the limitations of collecting operational data, it was not feasible to assess vibration with different occupants at the pilot, flight engineer, and crew chief stations. For several flight conditions multiple points were collected to observe the variability that may occur due to posture or activity. Large differences in the acceleration levels are not expected unless there are large differences between occupants’ anthropometry. If large differences are expected, then a more thorough investigation should be undertaken that includes representative occupants.

RECOMMENDATIONS

The following recommendations are made based on the results of this study:

1. Conduct periodic monitoring of the aircrew members by a flight surgeon, particularly focusing on reports of discomfort and pain in the back, hips, and buttocks areas, and numbness in the lower extremities during flight.
2. Conduct an epidemiological survey of the CV-22 crew population to identify potential health risks, particularly during active deployment in hostile environments. Review any previous surveys of V-22 and variants and evaluate for issues with discomfort, annoyance, pain, numbness, and health risk. Issues with anthropometry or occupant size should also be investigated.
3. Consider modifications to both the pilot and flight engineer seats in the cockpit to improve comfort and reduce vibration. Vibration levels may be influenced by the

seated posture, as well as the seat pan and seat back cushion design. The results of any previous surveys may provide information on seat design considerations. Future surveys should be tailored to include details on posture and anthropometric accommodation.

4. It was not clear whether there was a procedure for balancing the propeller blades on the CV-22. It was also not clear whether synchrophasing of the propellers was an option. Both of these processes have the potential for reducing aircraft vibration.

5. While based on the limited operational data collected in this study, the AVSS did not appear to have any predictable effect on the measured accelerations or on the overall weighted seat pan vibration during cruise. This issue should be further investigated.

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APPENDIX A: METHODS AND MATERIALS TABLES

Table A-1: Flight Test Conditions

Test Condition	Sortie/ Test Record	Altitude Ft. MSL	Airspeed KCAS	% RPM*	Nacelle Angle
Ground Taxi	A/1	0	A/R	100	A/R
Short Takeoff (STO)	A/1		A/R	100	60
Short Takeoff (STO)	B/1			103.8	75
Climb Conv Mode	A/1	4K-6K	110	100	60
Climb Apln Mode	A/1	4K-6K	150	84	0
Descent	A/1	10K	275	84	A/R
Cruise Apln Mode	A/3,A/3,A/3	10K, 7K, 5K	220	84	0
Cruise Apln Mode (FE upper door open)	A/1, A/1	7K, 5K	220	84	0
Cruise Apln Mode AVSS disabled	A/1	5K	220	84	0
Cruise Conv Mode	A/3, A/6**	5K, 3K	110	100	60
Cruise Conv mode (FE upper door open)	A/1,A/1	5K, 3K	110	100	60
Conversion	A/4, A/7***	5K, 3K	40-220	100-84	90-0
Conversion	A/3	5K	110-220	100-84	60-0
Conversion	A/3	3K	110-220	100-84	60-0
Re-Conversion	A/3, A/3	5K, 3K	220-110	84-100	0-60
Approach to IGE Hover	A/3, B/1	IGE	110-0	103.8	A/R
Approach to IGE Hover	B/1			100	
Approach to IGE Hover (Cabin door open)	B/3	IGE	110-0	103.8	A/R
Approach to IGE Hover (Cabin door open)	B/1			100	
Approach to OGE Hover	B/1	OGE	110-0	103.8	A/R
Approach to OGE Hover	B/1			100	
Approach to OGE Hover (Cabin door open)	B/1	OGE	110-0	103.8	A/R
Approach to OGE Hover (Cabin door open)	B/1			100	
IGE Hover	A/3, B/3	IGE	0	103.8	A/R
IGE Hover	B/3			100	
IGE Hover (FE upper door open)	A/1, B/1	IGE	0	103.8	A/R
IGE Hover (FE upper door open)	B/1			100	
IGE Hover (AVSS off)	A/1, B/1	IGE	0	103.8	A/R
IGE Hover (AVSS off)	B/1			100	
IGE Hover (Cabin door open)	A/3, B/3	IGE	0	103.8	A/R
IGE Hover (Cabin door open)	B/3			100	
OGE Hover	B/3	OGE	0	103.8	A/R
OGE Hover	B/3			100	
OGE Hover (FE upper door open)	B/1	OGE	0	103.8	A/R
OGE Hover (FE upper door open)	B/1			100	
Roll on Landing	B/1	500-0 AGL	110-A/R	100-104	A/R

*100% RPM=397 Revolutions Per Second (rotor speed); **Heavy (3 test points), Light (3 Test Points); ***Heavy (4 test points), Light (3 test points)

Table A-2: CV-22 Spectral Components

% RPM	SPECTRAL COMPONENT (Hz)					
	1P (PRF*)	2P	3P (BPF**)	6P	9P	12P
84	5.6	11.1	16.7	33.3	50.0	66.7
100	6.6	13.2	19.8	39.7	59.6	79.4
103.5	6.9	13.7	20.6	41.2	61.8	82.4

*PRF = Propeller Rotation Frequency; **BPF = Blade Passage Frequency
Note: These are approximate values based on 100% RPM = 397 revolutions per minute

APPENDIX B: RESULTS FIGURES AND TABLES

Table B-1: Pilot (PI) Comfort Assessment Based on the Mean Overall VTV

Test Condition	**Vibration Total Value (VTV) (ms^{-2} rms)**	**Comfort Reaction (ISO 2631-1: 1997)**	**Rating**
Ground Taxi	0.68	Fairly Uncomfortable	Marginal
Takeoff	0.75	Fairly Uncomfortable	Marginal
Climb Conv	1.14	Uncomfortable	Unsatisfactory
Climb Apln	0.65	Fairly Uncomfortable	Marginal
Conversion	0.64	Fairly Uncomfortable	Marginal
Reconversion	0.68	Fairly Uncomfortable	Marginal
Cruise Apln	0.76	Fairly Uncomfortable	Marginal
Cruise Conv	0.81	Fairly Uncomfortable - Uncomfortable	Marginal
Approach IGE	0.66	Fairly Uncomfortable	Marginal
IGE Hover	0.39	A Little Uncomfortable	Satisfactory
Approach OGE	0.54	Fairly Uncomfortable	Marginal
OGE Hover	0.29	Not Uncomfortable	Satisfactory
Descent	0.88	Fairly Uncomfortable - Uncomfortable	Marginal
Roll on Landing	0.72	Fairly Uncomfortable	Marginal

Table B-2: Flight Engineer (FE) Comfort Assessment Based on the Mean Estimated VTV

Test Condition	**Vibration Total Value (VTV) (ms^{-2} rms**	**Comfort Reaction (ISO 2631-1: 1997)**	**Rating**
Ground Taxi	0.56	Fairly Uncomfortable	Marginal
Takeoff	0.60	Fairly Uncomfortable	Marginal
Climb Conv	0.55	Fairly Uncomfortable	Marginal
Climb Apln	0.51	Fairly Uncomfortable	Marginal
Conversion	0.47	A Little Uncomfortable	Satisfactory
Reconversion	0.57	Fairly Uncomfortable	Marginal
Cruise Apln	0.48	A Little Uncomfortable	Satisfactory
Cruise Conv	0.58	Fairly Uncomfortable	Marginal
Approach IGE	0.5	Fairly Uncomfortable	Marginal
IGE Hover	0.32	A Little Uncomfortable	Satisfactory
Approach OGE	0.39	A Little Uncomfortable	Satisfactory
OGE Hover	0.25	Not Uncomfortable	Satisfactory
Descent	0.59	Fairly Uncomfortable	Marginal
Roll on Landing	0.63	Fairly Uncomfortable	Marginal

Table B-3: Crew Chief (CC) Comfort Assessment Based on the Mean Overall VTV

Test Condition	**Vibration Total Value (VTV) (ms^{-2} rms**	**Comfort Reaction (ISO 2631-1: 1997)**	**Rating**
Ground Taxi	0.88	Fairly Uncomfortable - Uncomfortable	Marginal
Takeoff	0.58	Fairly Uncomfortable	Marginal
Climb Conv	1.00	Fairly Uncomfortable - Uncomfortable	Marginal
Climb Apln	0.34	A Little Uncomfortable	Satisfactory
Conversion	0.71	Fairly Uncomfortable	Marginal
Reconversion	0.84	Fairly Uncomfortable - Uncomfortable	Marginal
Cruise Apln	0.37	A Little Uncomfortable	Satisfactory
Cruise Conv	0.51	Fairly Uncomfortable	Marginal
Approach IGE	0.69	Fairly Uncomfortable	Marginal
IGE Hover	0.56	Fairly Uncomfortable	Satisfactory
Approach OGE	0.57	Fairly Uncomfortable	Marginal
OGE Hover	0.37	A Little Uncomfortable	Satisfactory
Descent	0.57	Fairly Uncomfortable	Marginal
Roll on Landing	0.42	A Little Uncomfortable	Satisfactory

Table B-4. CV-22 Cruise Airplane Mode Exposure Duration Limits Based on Weighted Seat Pan Z Accelerations and Seat Pan VTV

Durations listed as Satisfactory fall below the lower boundary of the ISO 2631-1: 1997 Health Guidance Caution Zones; durations listed as Marginal fall between the lower and upper boundaries (inclusive); durations beyond the upper boundary are considered Unsatisfactory.

CRUISE APLN MODE	PILOT		FLIGHT ENGINEER		CREW CHIEF	
	DURATION LIMITS (Hours) BASED ON SEAT PAN Z					
	Satisfactory	Marginal	Satisfactory	Marginal	Satisfactory	Marginal
10K Rep 1	<2.4	9.4	<6.4	25.7	<11.4	45.4
10K Rep 2	<2.4	9.6	<6.5	26.1	<11.4	45.6
10K Rep 3	<2.5	10.1	<7.0	27.9	<12.5	49.9
7K Rep 1	<2.8	11.2	<6.1	24.3	<16.7	66.9
7K Rep 2	<2.8	11.1	<6.2	24.8	<15.1	60.4
7K Rep 3	<2.6	10.4	<6.7	26.7	<16.3	65.0
7K FE Door Open	<2.6	10.6	<5.4	21.8	<14.5	58.2
5K Rep 1	<3.0	12.2	<8.5	34.2	<20.3	81.3
5K Rep 2	<3.2	12.8	<7.7	30.9	<20.4	81.7
5K Rep 3	<3.1	12.3	<8.1	32.3	<20.0	80.0
5K FE Door Open	<3.3	13.4	<7.5	30.1	<21.6	86.4
5k AVSS Off	<3.2	12.7	<7.0	28.1	<20.8	83.2
Mean ±1 SD	2.8±0.33	11.3±1.3	6.9±0.90	27.7±3.6	16.8±3.8	67.0±15.3
	DURATION LIMITS (Hours) BASED ON SEAT PAN VTV					
	Satisfactory	Marginal	Satisfactory	Marginal	Satisfactory	Marginal
10K Rep 1	<2.3	9.2	<6.0	23.8	<9.9	39.5
10K Rep 2	<2.3	9.4	<6.1	24.3	<9.9	39.7
10K Rep 3	<2.5	9.9	<6.5	25.9	<10.8	43.0
7K Rep 1	<2.7	10.9	<5.8	23.1	<14.0	56.0
7K Rep 2	<2.7	10.8	<5.8	23.4	<12.9	51.5
7K Rep 3	<2.6	10.2	<6.2	25.0	<13.5	54.2
7K FE Door Open	<2.7	10.3	<5.1	20.6	<12.3	49.1
5K Rep 1	<3.0	11.9	<8.0	31.9	<16.7	66.9
5K Rep 2	<3.1	12.5	<7.3	29.1	<16.9	67.7
5K Rep 3	<3.0	12.0	<7.6	30.4	<16.7	66.7
5K FE Door Open	<3.3	13.0	<7.1	28.4	<17.6	70.3
5k AVSS Off	<3.1	12.4	<6.6	26.5	<16.9	67.6
Mean ±1 SD	2.8±0.32	11.0±1.3	6.5±0.84	26.0±3.4	14.0±2.9	56.0±11.6

Table B-5. CV-22 Cruise Conversion Mode Exposure Duration Limits Based on Weighted Seat Pan Z Accelerations and Seat Pan VTV

Durations listed as Satisfactory fall below the lower boundary of the ISO 2631-1: 1997 Health Guidance Caution Zones; durations listed as Marginal fall between the lower and upper boundaries (inclusive); durations beyond the upper boundary are considered Unsatisfactory.

CRUISE CONV MODE	PILOT		FLIGHT ENGINEER		CREW CHIEF	
	DURATION LIMITS (Hours) BASED ON SEAT PAN Z					
	Satisfactory	Marginal	Satisfactory	Marginal	Satisfactory	Marginal
5K Rep 1	<3.0	12.0	<4.8	19.0	<4.8	19.4
5K Rep 2	<3.4	13.6	<4.8	19.3	<4.4	17.4
5K Rep 3	<2.6	10.3	<4.4	17.7	<4.2	16.8
5K FE Door Open	<2.6	10.2	<4.1	16.4	<6.0	24.1
3K Rep 1A	<3.1	12.3	<4.8	19.1	<9.5	38.0
3K Rep 2A	<3.0	11.8	<4.8	19.4	<13.4	53.5
3K Rep 3A	<3.1	12.3	<5.1	20.6	<8.8	35.3
3K FE Door Open A	<2.8	11.2	<4.5	17.9	<11.1	44.2
3K Rep 1B	<4.8	19.0	<7.9	31.5	<7. 9	31.5
3K Rep 2B	<3.8	15.2	<8.0	32.2	<8. 6	34.5
3K Rep 3B	<4.5	18.0	<6.8	27.2	<10. 3	41.3
3K FE Door Open B	<4.3	17.3	--	--	<10. 3	41.2
Mean ± 1 SD	3.4±0.76	13.6±3.0	5.5±1.4	21.8±5.6	8.3±2.9	33.1±11.6
	DURATION LIMITS (Hours) BASED ON SEAT PAN VTV					
	Satisfactory	Marginal	Satisfactory	Marginal	Satisfactory	Marginal
5K Rep 1	<2.5	9.8	<4.0	15.9	<4.3	17.3
5K Rep 2	<2.8	11.0	<4.0	16.2	<3.9	15.6
5K Rep 3	<2.2	8.7	<3.8	15.1	<3.8	15.2
5K FE Door Open	<2.2	8.6	<3.5	14.1	<5.2	20.8
3K Rep 1A	<2.6	10.4	<4.1	16.5	<7.9	31.7
3K Rep 2A	<2.5	9.9	<4.1	16.4	<10.1	40.5
3K Rep 3A	<2.5	10.1	<4.3	17.1	<7.2	29.0
3K FE Door Open A	<2.4	9.6	<3.9	15.6	<9.0	35.8
3K Rep 1B	<3.7	15.0	<6.3	25.2	<6.6	26.2
3K Rep 2B	<3.1	12.5	<6.4	25.6	<7.0	28.2
3K Rep 3B	<3.5	14.2	<5.6	27.4	<8.1	32.3
3K FE Door Open B	<3.5	13.9	-	-	<8.4	33.6
Mean ± 1 SD	2.8±0.55	11.1±2.2	4.5±1.0	18.2±4.1	6.8±2.1	27.2±8.3

Condition A: Fuel Wt = 7840 lbs
Condition B: Fuel Wt = 3128 lbs

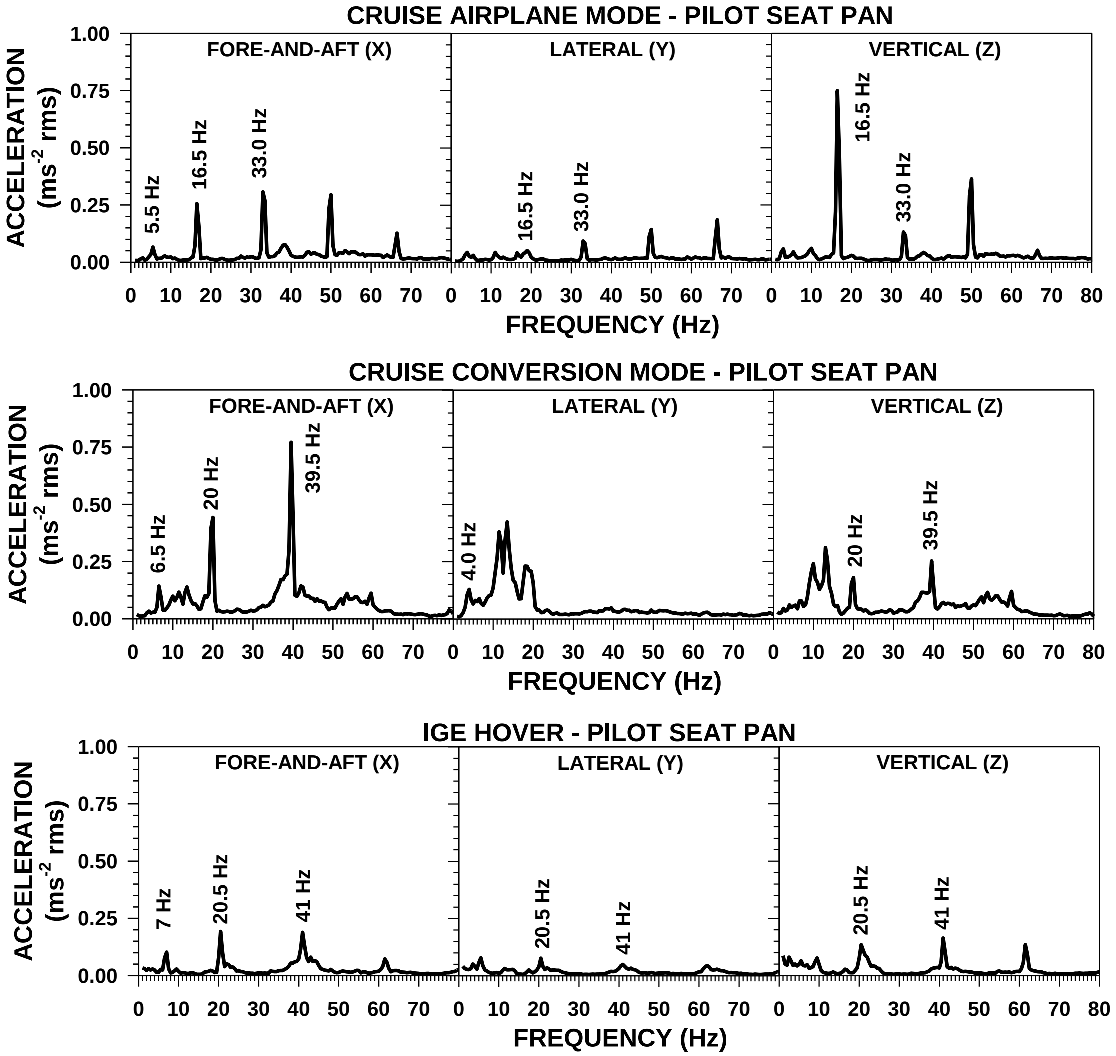


Figure B-1a. Pilot (PI) Seat Pan Acceleration Spectra

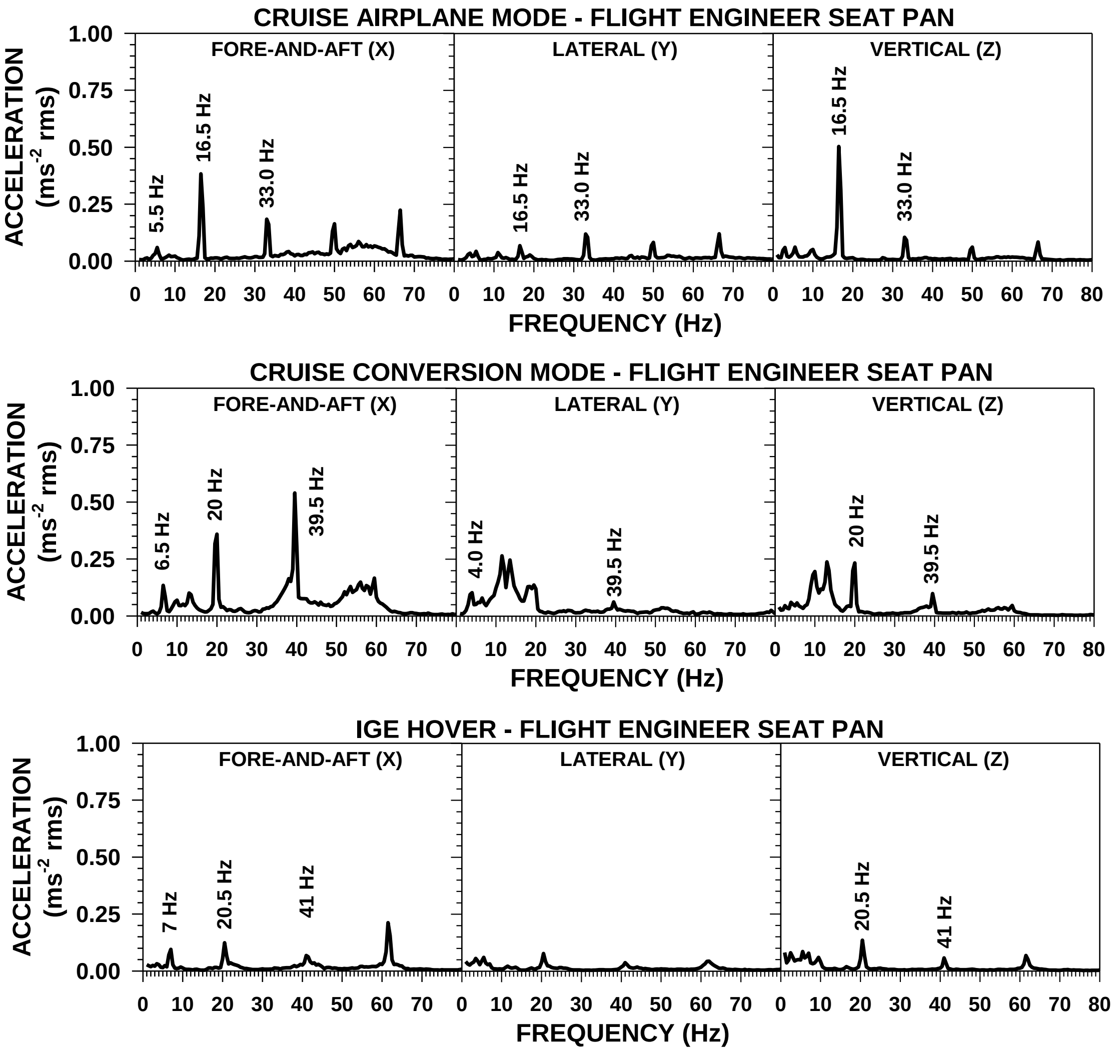


Figure B-1b. Flight Engineer (FE) Seat Pan Acceleration Spectra

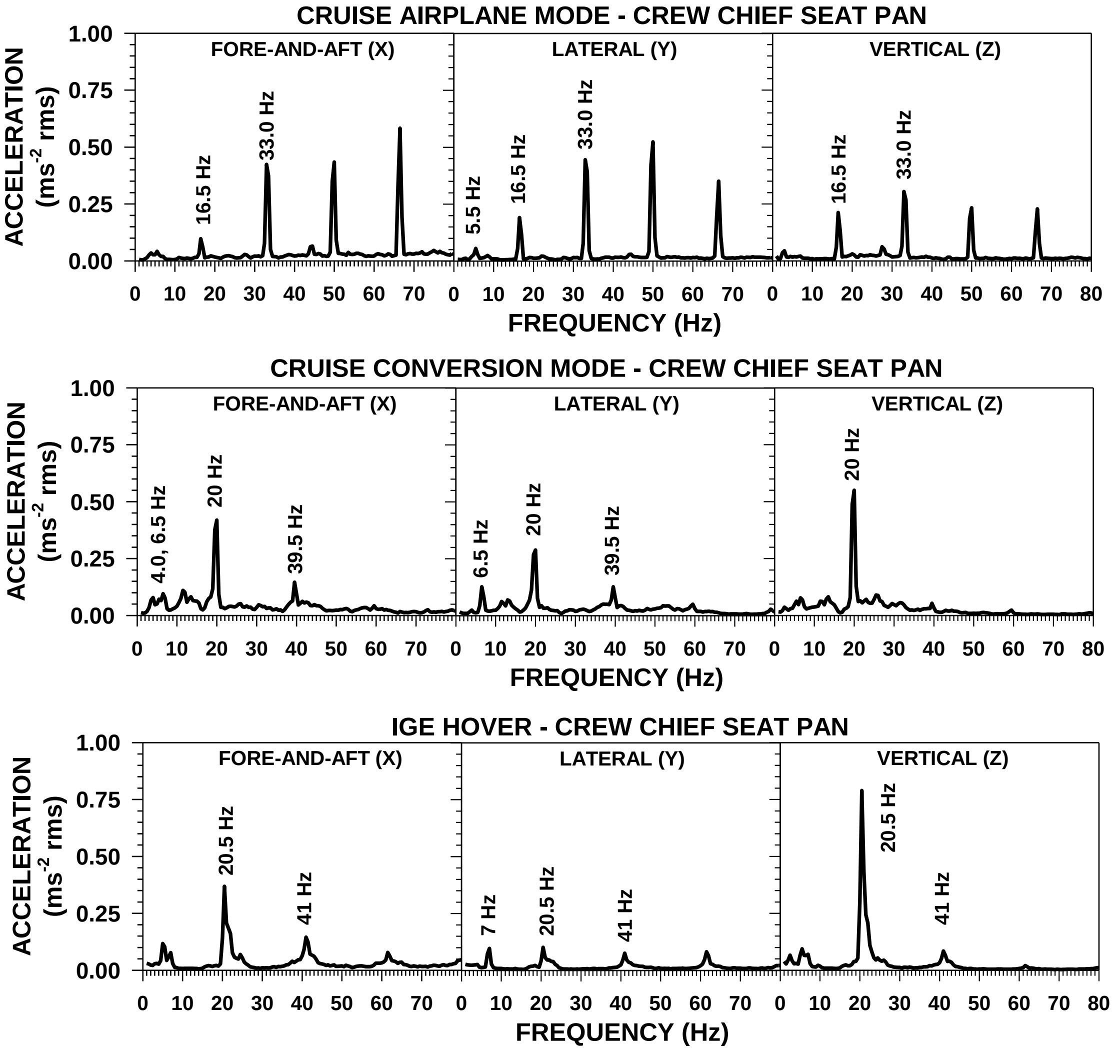


Figure B-1c. Crew Chief (CC) Seat Pan Acceleration Spectra

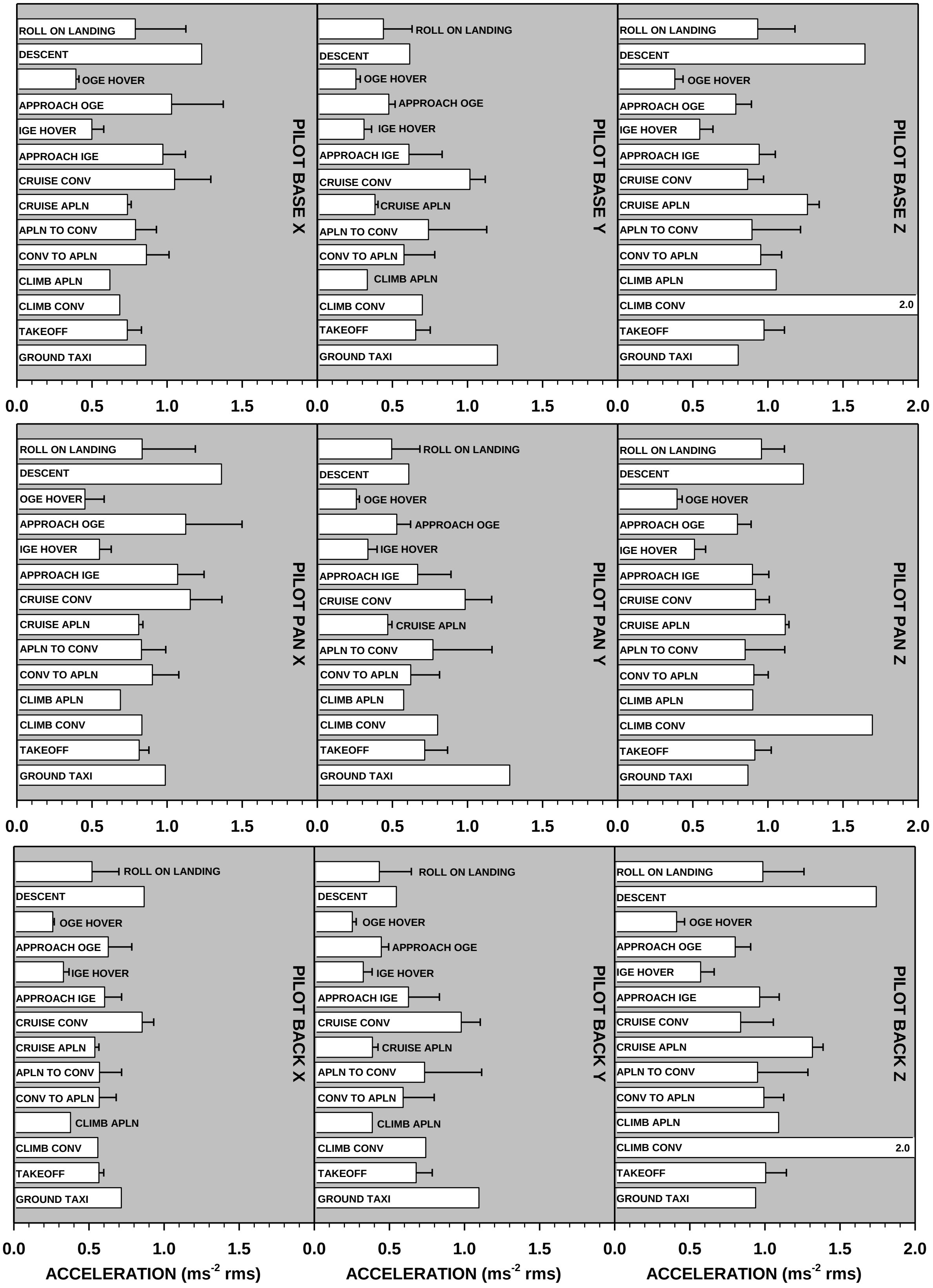


Figure B-2a Pilot (PI) Mean Overall (1 – 80 Hz) Rms Acceleration Levels ± 1 SD (for multiple points)

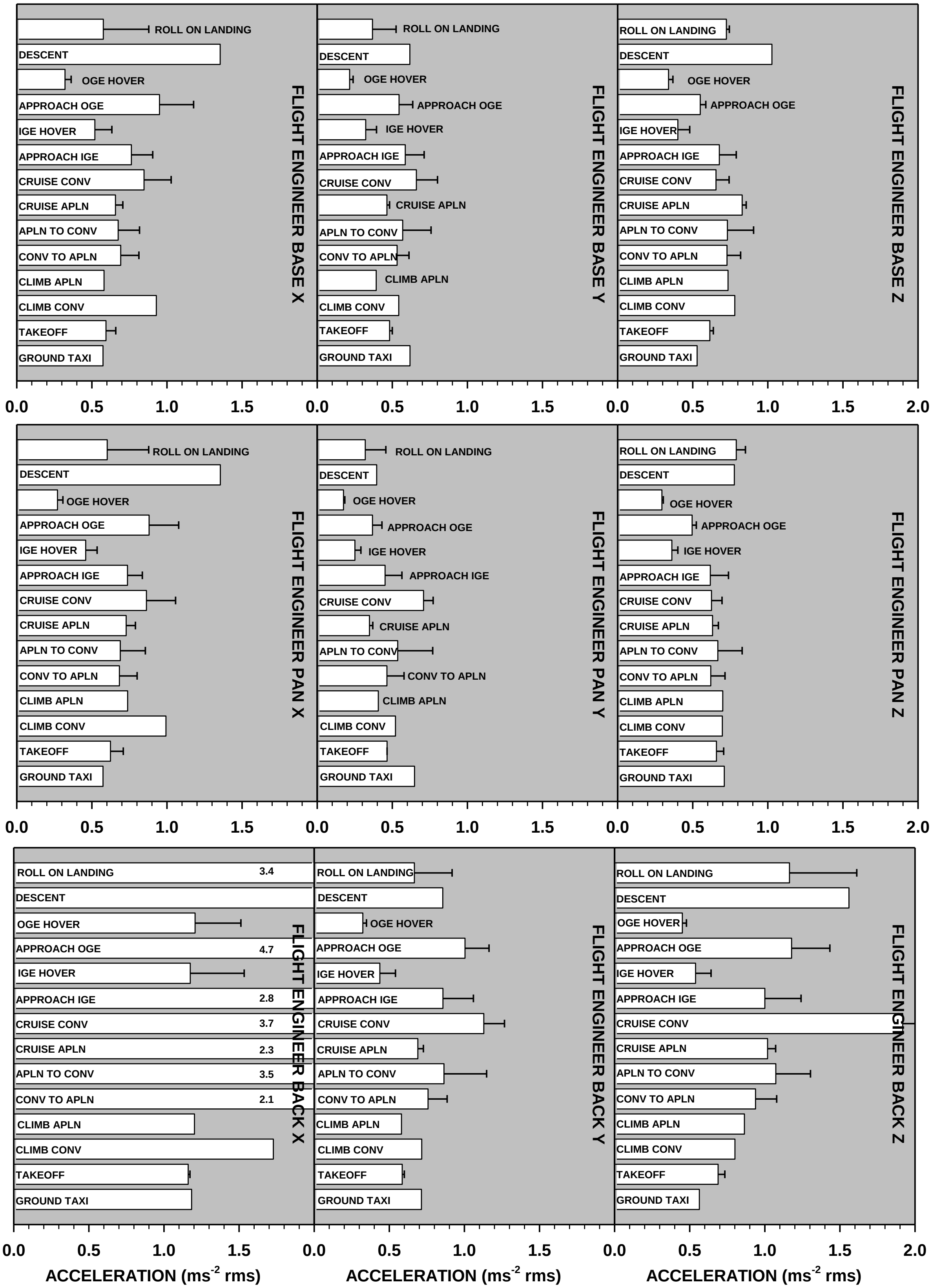


Figure B-2b Flight Engineer (FE) Mean Overall (1 – 80 Hz) Rms Acceleration Levels ± 1 SD (for multiple points)

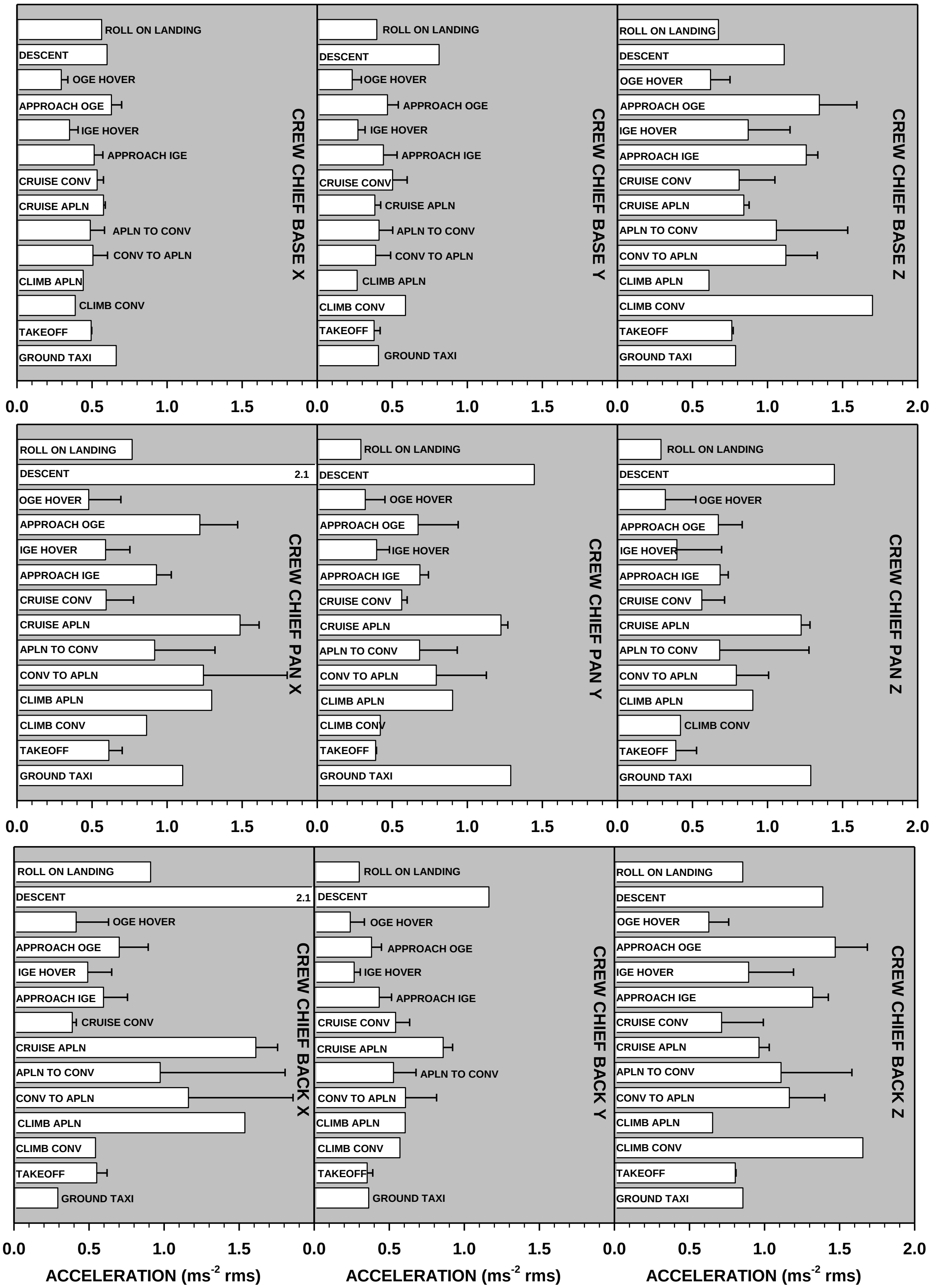


Figure B-2c Crew Chief (CC) Mean Overall (1 – 80 Hz) Rms Acceleration Levels ± 1 SD (for multiple points)

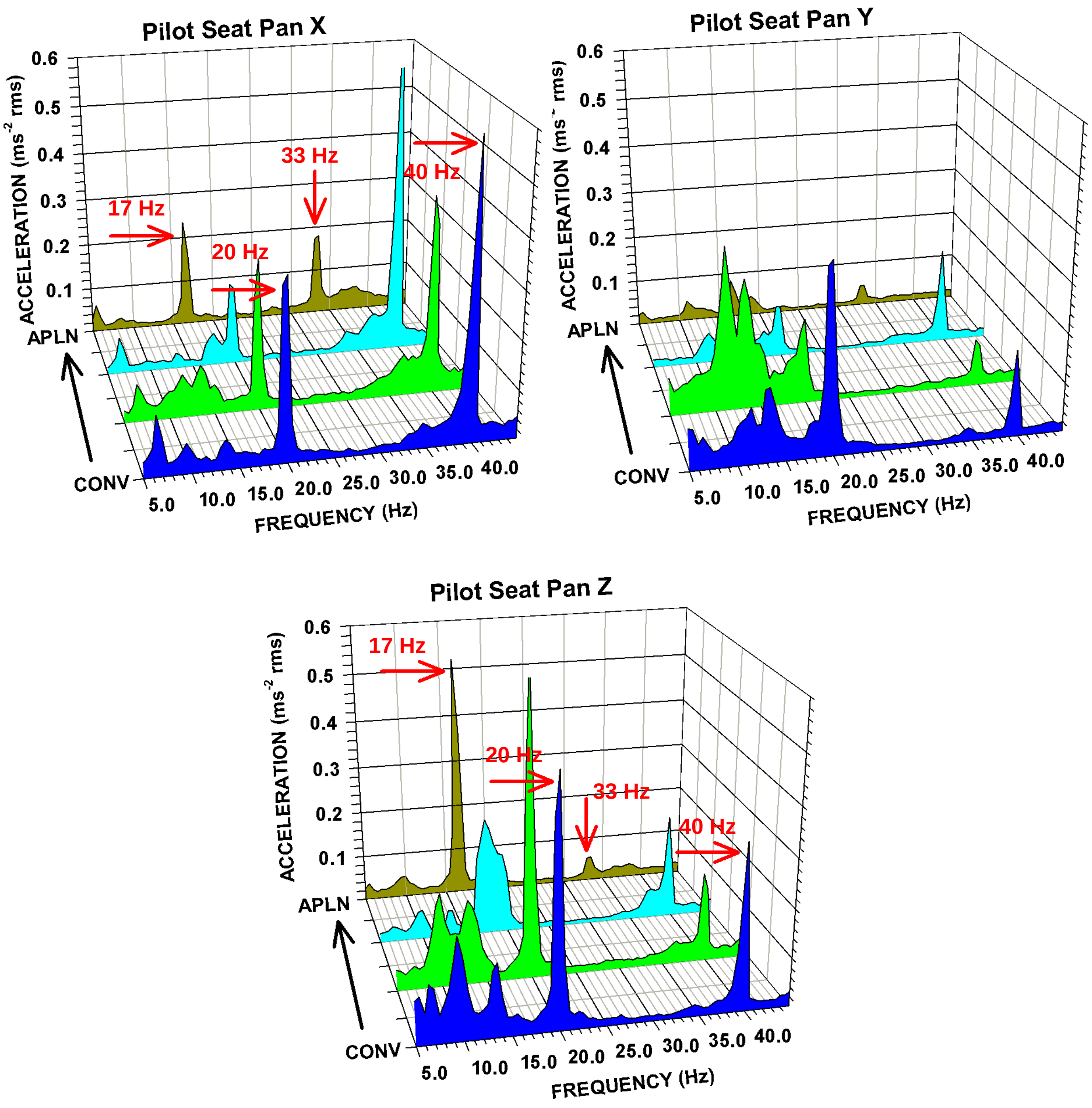


Figure B-3. Pilot Seat Pan Frequency Spectra During Transition from Conversion Mode to Airplane Mode (Conversion)

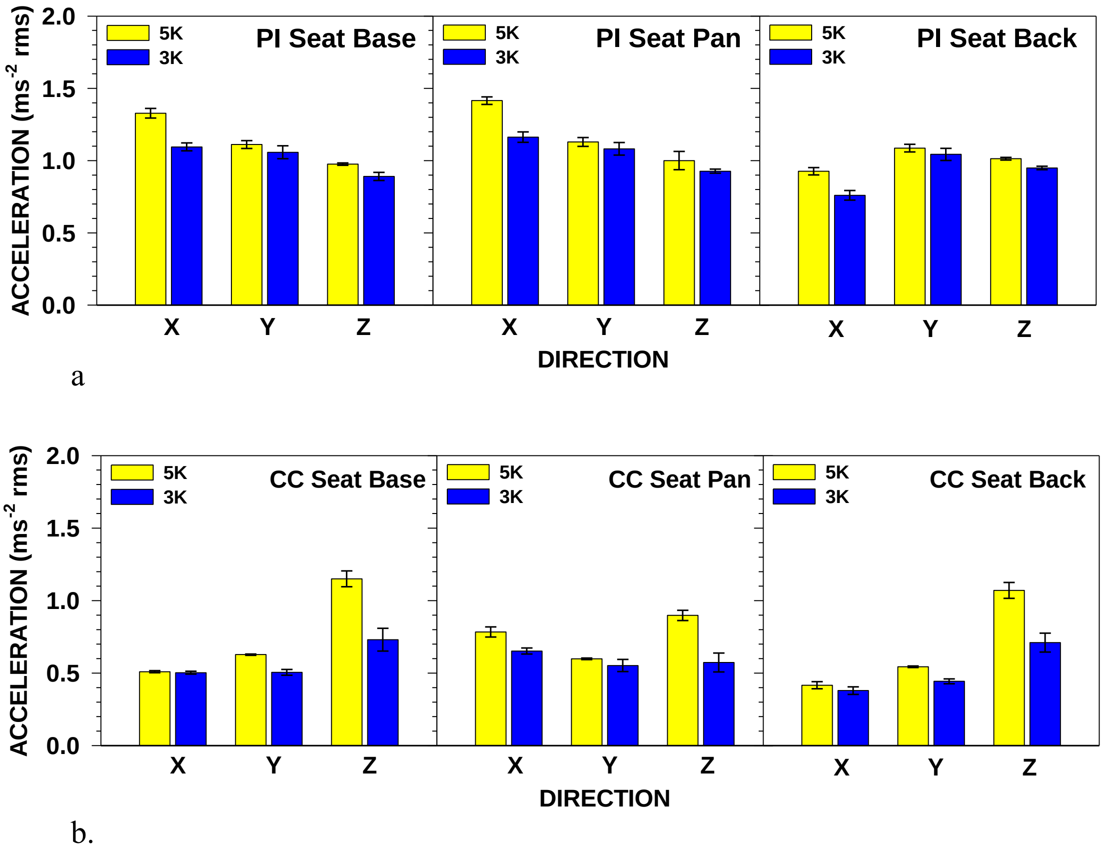


Figure B-4. Mean Overall Acceleration Levels ±1 SD (for multiple points) During Cruise Conversion Mode at 5K and 3K Ft MSL. a. Pilot Station (PI), b. Crew Chief Station (CC)

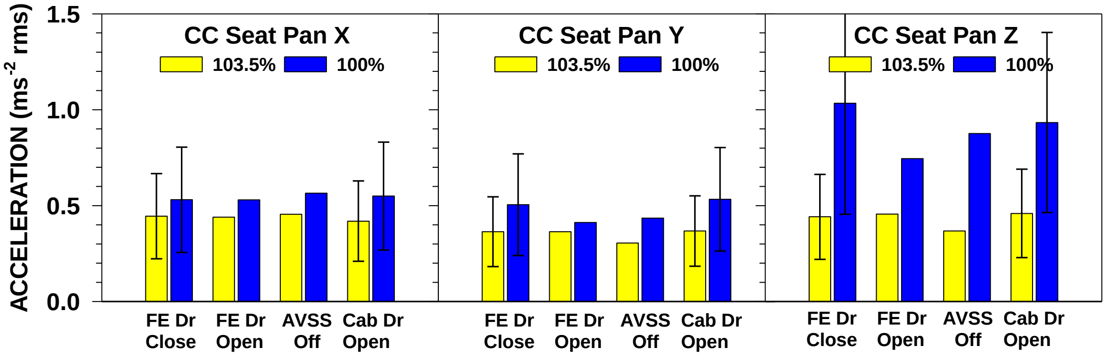


Figure B-5. Crew Chief (CC) Mean Overall Seat Pan Acceleration Levels ±1 SD (for multiple points) During IGE Hover at Engine Speeds 103.5% and 100%

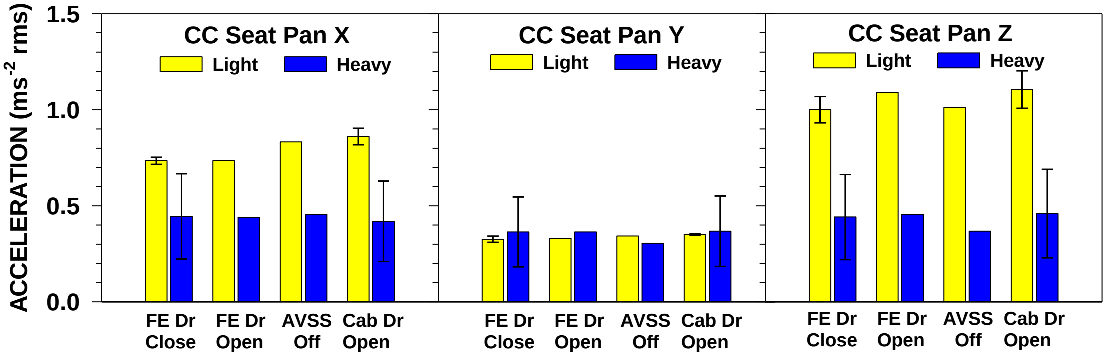


Figure B-6. Crew Chief (CC) Mean Overall Seat Pan Acceleration Levels ± 1 SD (for multiple points) for the Light (5850 lbs fuel) and Heavy (10348 lbs fuel) Aircraft During IGE Hover

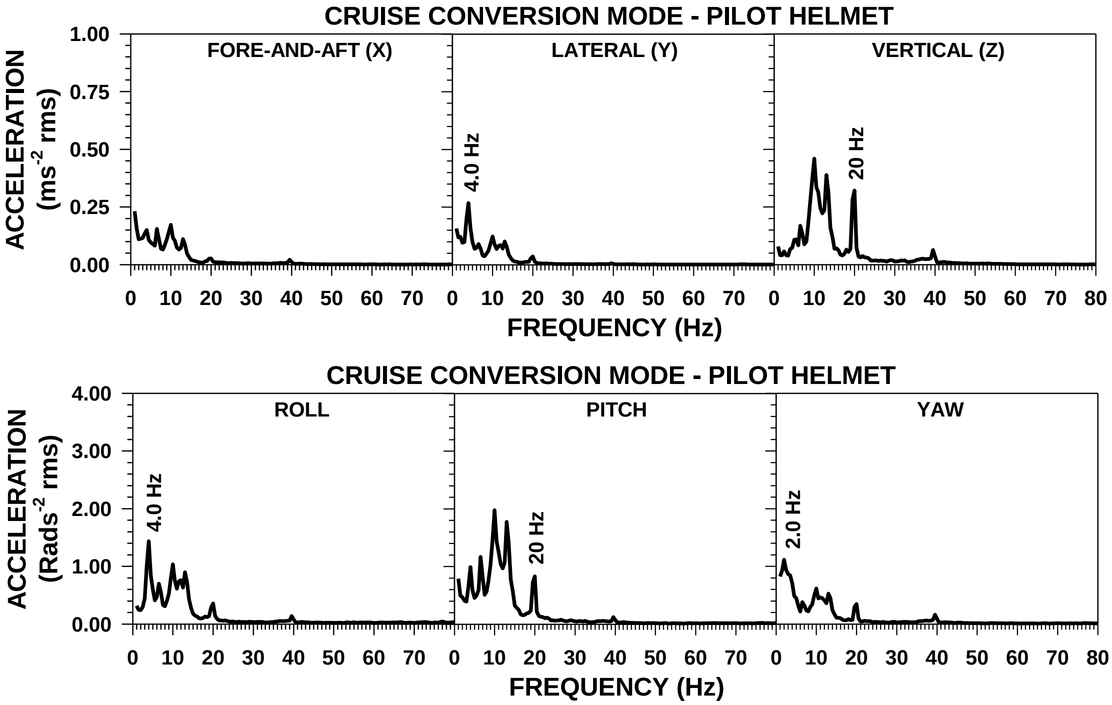


Figure B-7. Pilot Helmet Translational and Rotational Acceleration Spectra

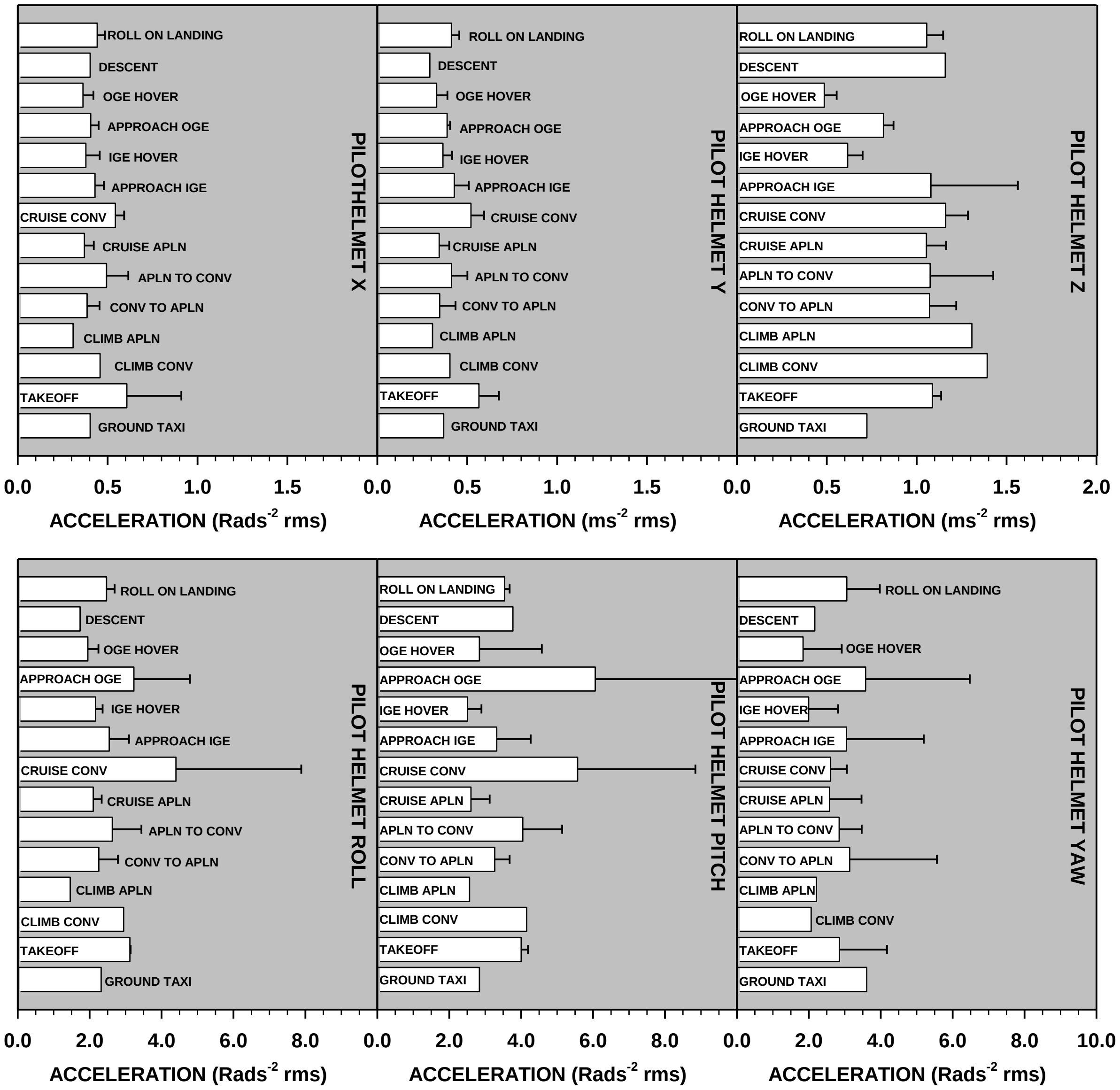


Figure B-8. Pilot Helmet Mean Overall (1 – 80 Hz) Translational and Rotational Rms Acceleration Levels ± 1 SD (for multiple points)

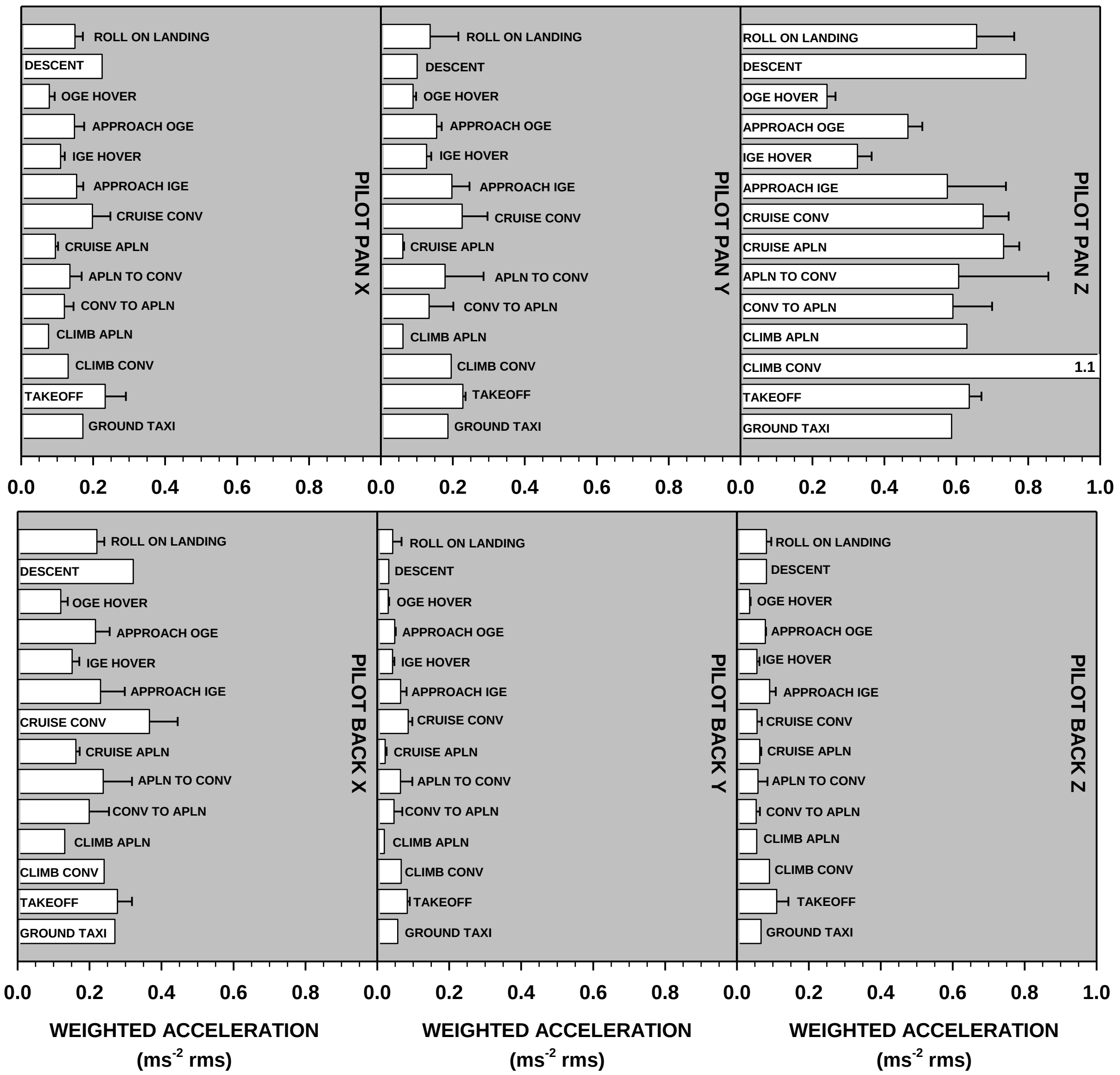


Figure B-9a. Pilot (PI) Mean Weighted Overall Seat Pan and Seat Back Accelerations ± 1 SD (for multiple points)

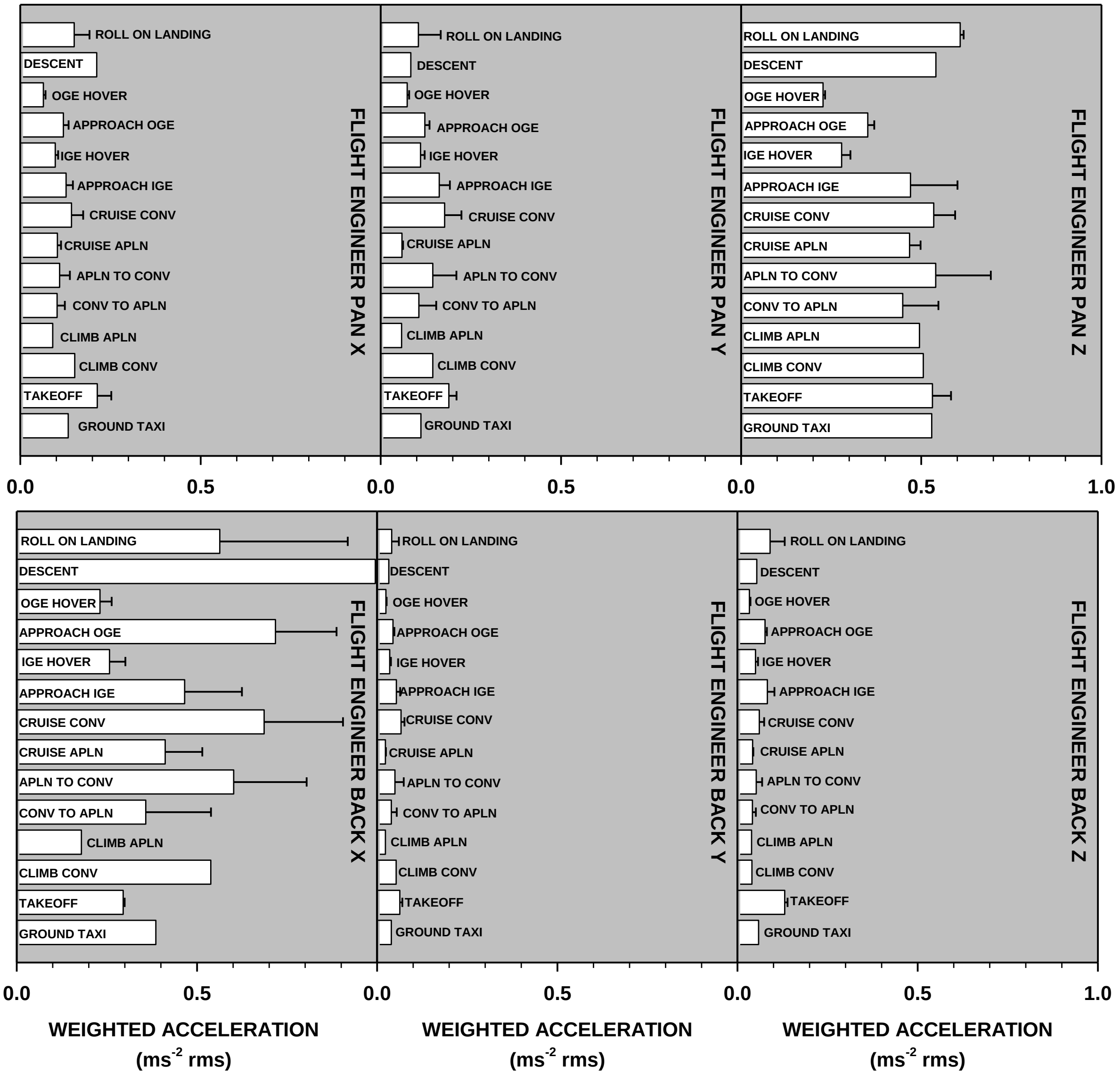


Figure B-9b. Flight Engineer (FE) Mean Weighted Overall Seat Pan and Seat Back Accelerations ± 1 SD (for multiple points)

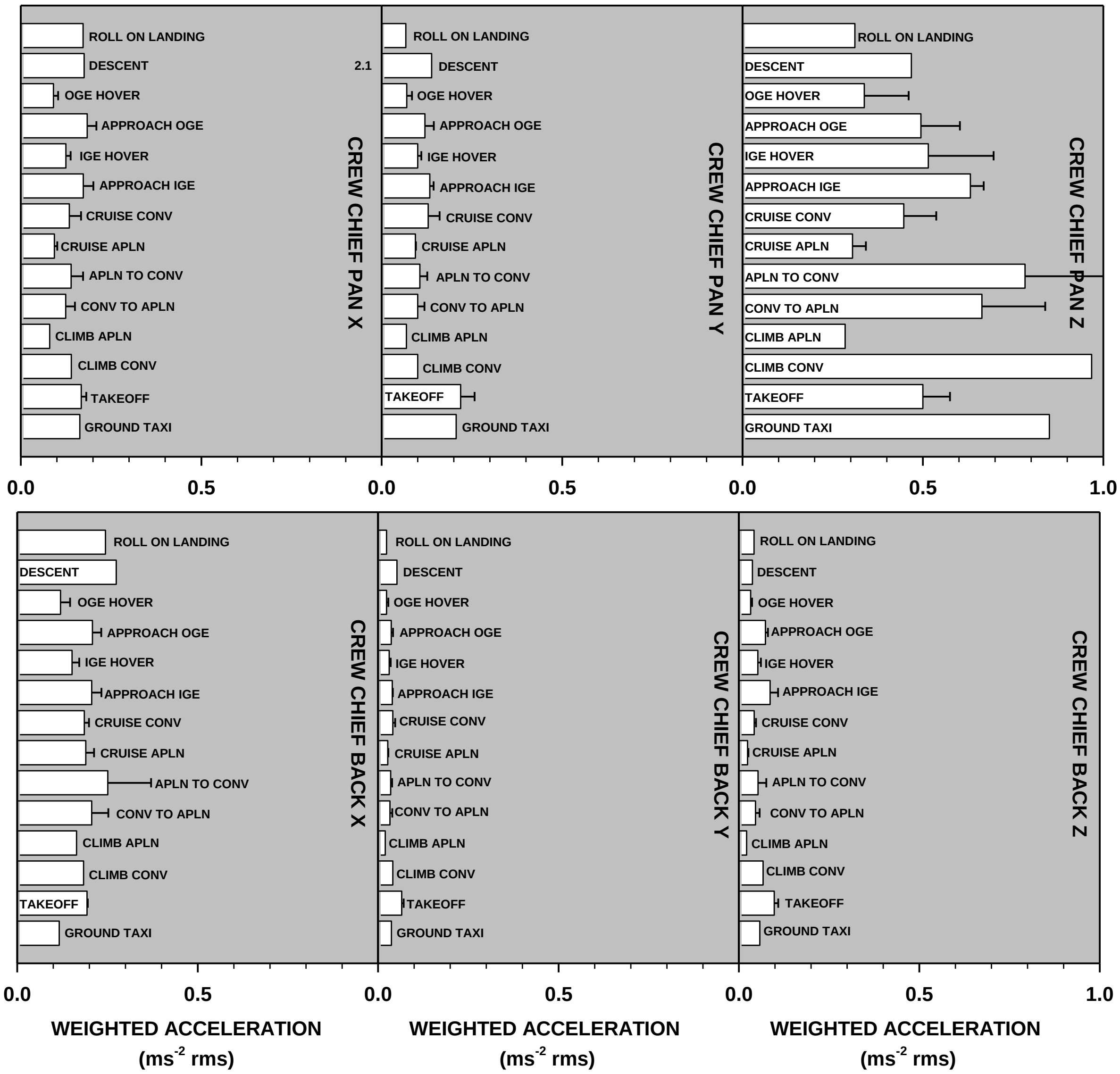


Figure B-9c. Crew Chief (CC) Mean Weighted Overall Seat Pan and Seat Back Accelerations ± 1 SD (for multiple points)

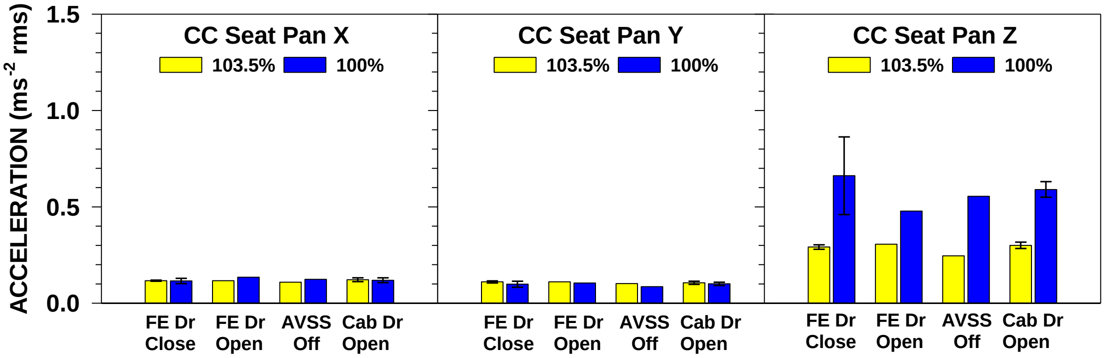


Figure B-10. Crew Chief (CC) Mean Weighted Overall Seat Pan Acceleration Levels ±1 SD (for multiple points) During IGE Hover at Engine Speed 103.5% and 100%

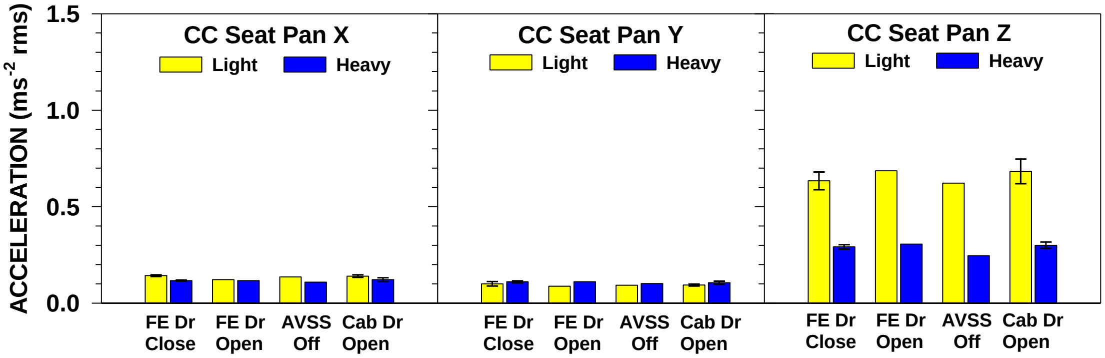


Figure B-11. Crew Chief (CC) Mean Overall Weighted Seat Pan Acceleration Levels ± 1 SD (for multiple points) for the Light (5850 lbs fuel) and Heavy (10348 lbs fuel) Aircraft

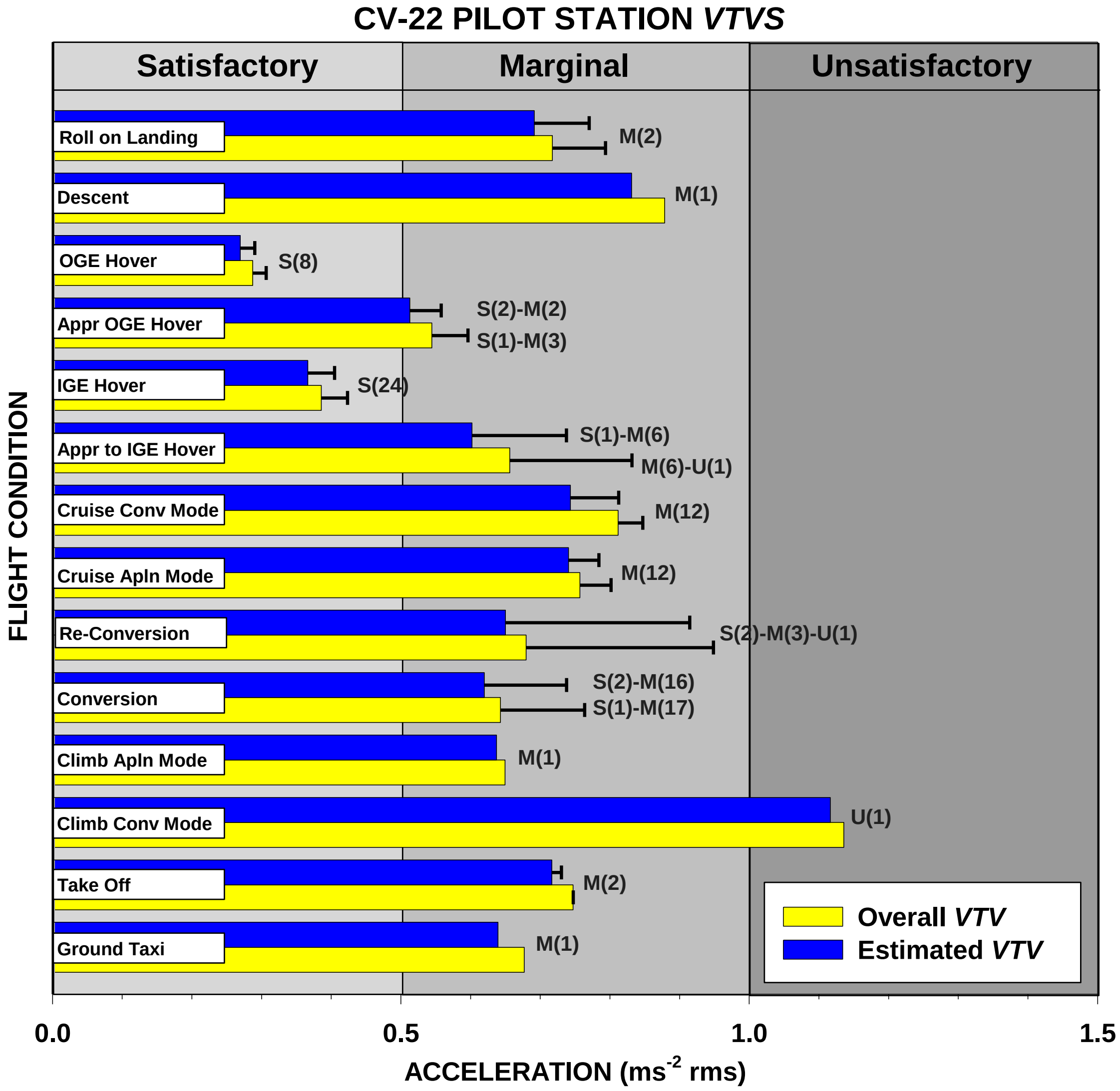


Figure B-12a. Pilot (PI) Mean Vibration Total Values (*VTVs*) ± 1 SD (for multiple points).

Total number of test points and ratings are given to the right of the bar. (Total Number of Test Points = 90)

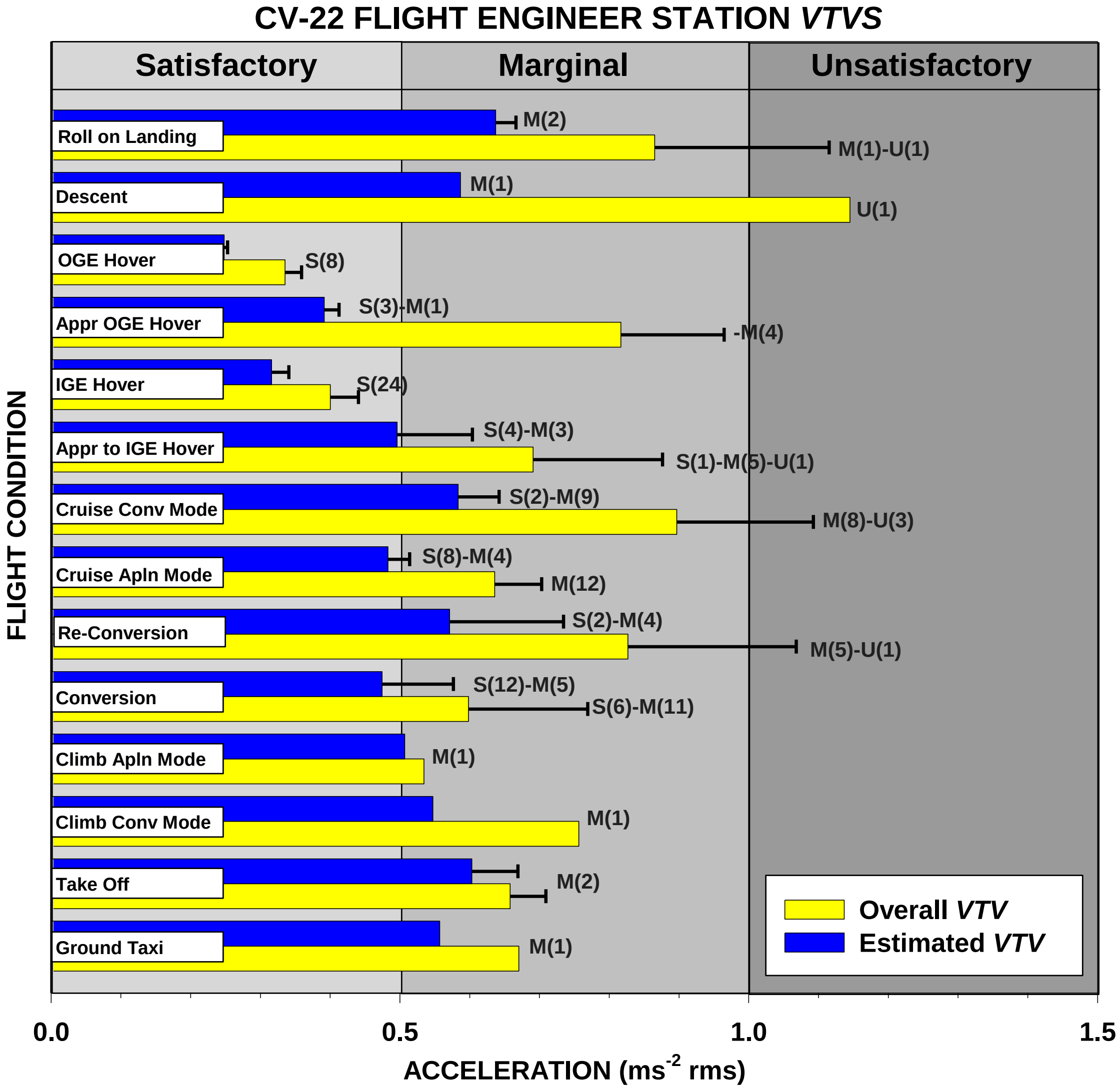


Figure B-12b. Flight Engineer (FE) Mean Vibration Total Values (*VTVs*) ± 1 SD (for multiple points).

Total number of test points and ratings are given to the right of the bar. (Total Number of Test Points = 97)

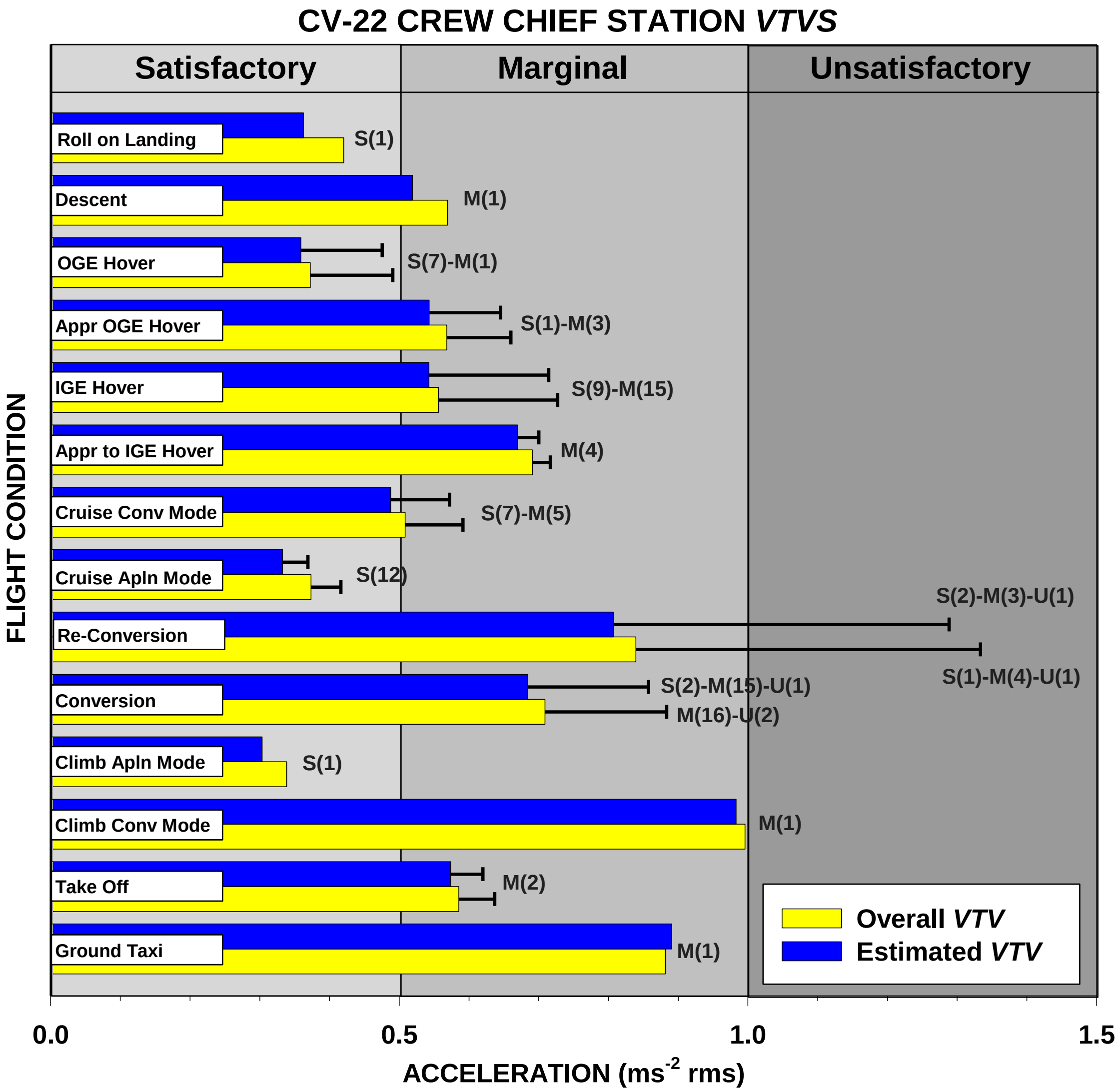


Figure B-12c. Crew Chief (CC) Mean Vibration Total Values (*VTVs*) ± 1 SD (for multiple points).

Total number of test points and ratings are given to the right of the bar. (Total Number of Test Points = 95)

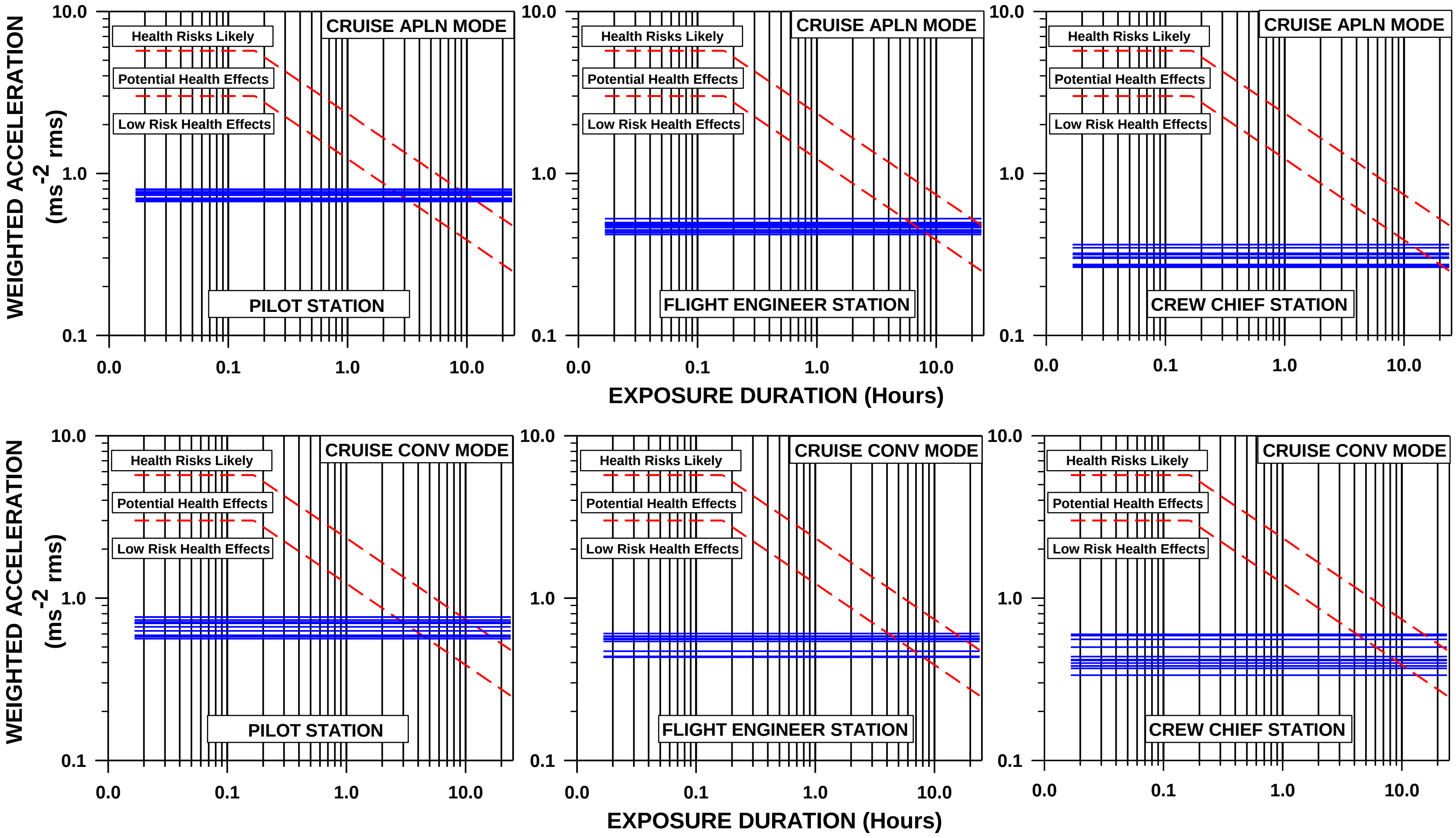
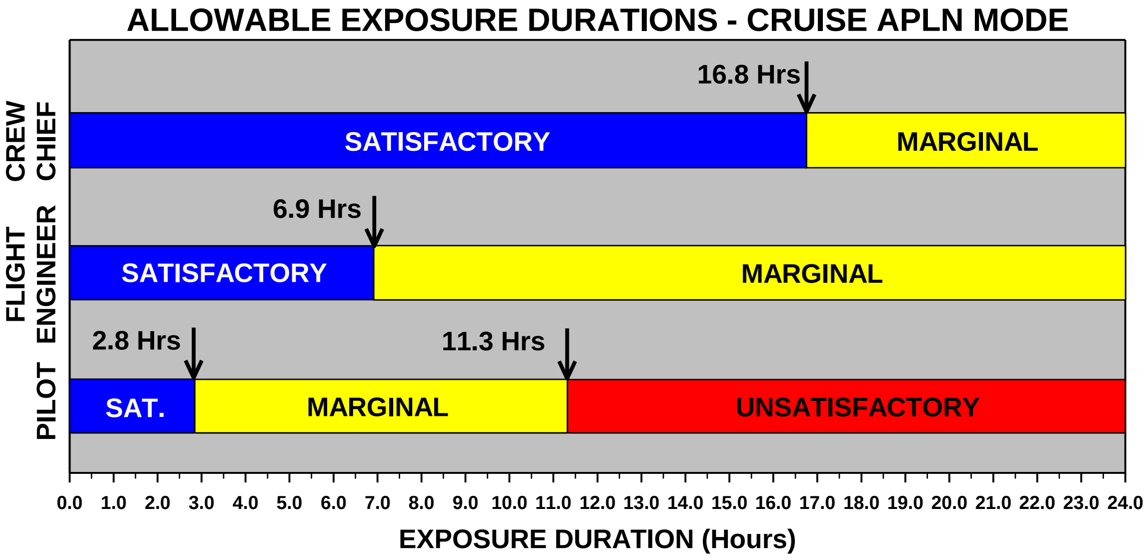
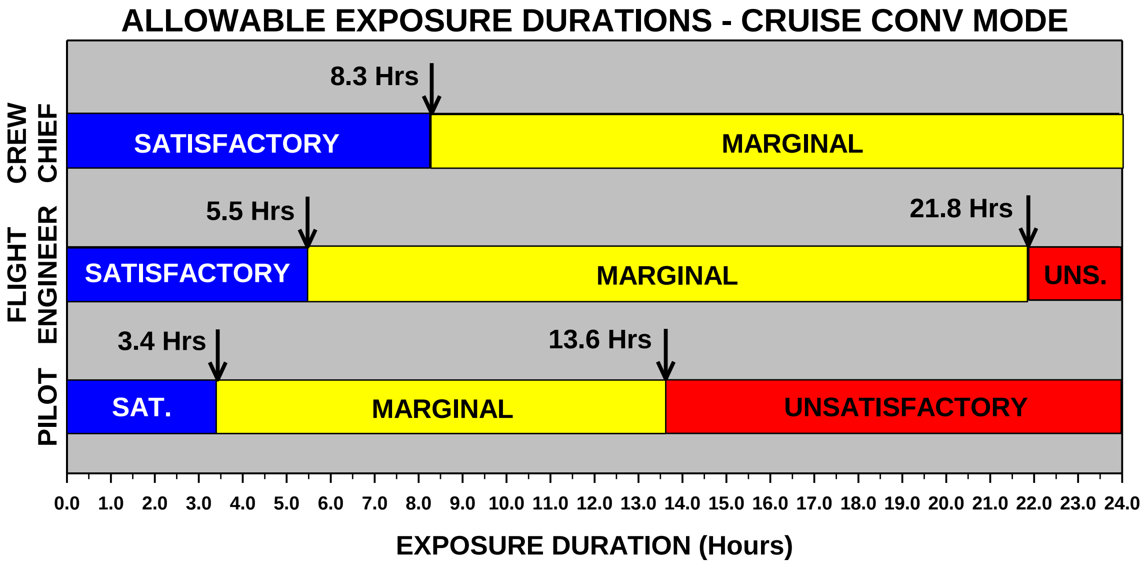


Figure B-13. ISO Health Guidance Caution Zones and Weighted Seat Pan Accelerations During Cruise Flight



a.



b.

Figure B-14. Mean Allowable Exposure Durations Based on the Evaluation Criteria for Health Risk. a. Cruise Apln Mode, b. Cruise Conv Mode

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE OHIO 45433-7008

26 July 11

MEMORANDUM FOR DTIC-OQ
ATTN: LARRY DOWNING
8725 JOHN J. KINGMAN ROAD
FORT BELVOIR, VA 22060-6218

FROM: 711 HPW/OMCA (STINFO)
2947 Fifth Street
Wright-Patterson AFB, OH 45433-7913

SUBJECT: Request to Change the Distribution Statement on a Technical Report

This memo documents the requirement for DTIC to change the distribution statement on the following technical report from distribution statement B to A. Approved for Public Release; distribution is unlimited.

AD Number: ADB345174
Publication number: AFRL-RH-WP-TR-2008-0095
Title: CV-22 Human Vibration Evaluation

Reason for request: The current Distribution B limits release of the data, methods, and conclusions of this study to US Gov Agencies Only. The objective was to characterize and assess human vibration exposure aboard the CV-22 Osprey in accordance with current international standards. By changing from Distribution B to Distribution A, this report can further benefit the US military by providing human vibration information to other non-government agencies, contractors, industry, and/or academia who can apply this information in developing and designing improved human interfaces (helmets, seats, displays) that mitigate the effects of the characteristic vibration. These data can also be use by others to recreate the environment for integration into more robust and realistic simulators for training aircrew and assessing performance capabilities in a dynamic environment. In addition, the approach to data collection and evaluation used in this study, including the use of the international standard which is also referenced in MIL-STD 1472, may improve and create more consistency in the collection and assessment of similar types of data, particularly with regard to aircraft.

Donald Denio
DONALD DENIO
STINFO Officer
711th Human Performance Wing