



AFRL-RH-WP-TR-2024-0036

**MILITARY AIRCRAFT SEAT VIBRATION MITIGATION
PROOF OF CONCEPT (POC) TESTING AND ANALYSIS
METHODOLOGY**

**Suzanne D. Smith, PhD
Consultant, Infoscitex
Air Force Research Laboratory**

**MAY 2024
Interim Report**

Distribution Statement A: Approved for public release. Distribution is unlimited.

See additional restrictions described on inside pages

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

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory Public Affairs Office and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (<http://www.dtic.mil>).

AFRL-RH-WP- TR-2024-0036 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

PETER P. LE, PhD
Lead, Aerospace Operations Chronic
Health Risk Modeling Line of Effort
Biomedical Impact of Flight Branch
Air and Space Biosciences Division

CHRISTOPHER J. DOOLEY
Core Research Area Lead, Biomedical
Impact of Air and Space
Biomedical Impact of Flight Branch
Air and Space Biosciences Division

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY) 22-05-2024		2. REPORT TYPE Interim		3. DATES COVERED (From - To) 1 April 2021 – 30 April 2024
4. TITLE AND SUBTITLE Military Aircraft Seat Vibration Mitigation Proof-of-Concept (PoC) Testing and Analysis Methodology			5a. CONTRACT NUMBER FA8650-20-F-6209 0002 FA8650-20-D-6207(IDIQ)	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER 62202F	
6. AUTHOR(S) Suzanne D. Smith*			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER H11N	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) *Consultant, Infoscitex, DCS, WPAFB, OH 2800 Ascani Street, Bldg. 824, Area B Wright-Patterson AFB OH 45433-7947			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Materiel Command Air Force Research Laboratory 711th Human Performance Wing Human Effectiveness Directorate Air and Space Biosciences Division Biomedical Impact of Flight Branch Wright-Patterson AFB OH 45433			10. SPONSOR/MONITOR'S ACRONYM(S) 711 HPW/RHBF	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RH-WP-TR-2024-0036	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.				
13. SUPPLEMENTARY NOTES AFRL-2024-3184, cleared 10 July 2024.				
14. ABSTRACT This document presents a military aircraft seat vibration mitigation proof-of-concept (PoC) methodology and capability established within the Air Force Research Laboratory (AFRL) 711th Human Performance Wing (711 HPW) for human-occupied laboratory test/analysis of vibration mitigation seating system concepts. The methodology specifically targets military rotary-wing/tilt-rotor aircraft but can be extended to military fixed-wing propeller aircraft. It specifies the recommended facility and instrumentation requirements, test regime, and data collection/analysis processes and procedures and is packaged for quality, time, and cost effectiveness. The development of this PoC methodology leveraged the studies conducted by the AFRL 711 HPW. The first study was conducted in 2018 (Smith, S.D., et al., 2019) and is used to illustrate the analyses that have been explored in the development of the PoC methodology. Three additional studies were conducted between 2021 and 2023. The studies included a pilot seat and cabin seat designed for use in a fixed-wing propeller aircraft, and a pilot seat designed for a helicopter. The reports for these studies have not been cleared for public release at this time. This document is intended as a user guide for military aircraft seat vibration mitigation PoC testing and analysis for improving seat design where further mitigation may be warranted prior to conducting				
15. SUBJECT TERMS Human vibration, helicopters, health risk assessment, discomfort				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 47
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		19a. NAME OF RESPONSIBLE PERSON Peter P. Le
				19b. TELEPHONE NUMBER (include area code)

TABLE OF CONTENTS

LIST OF FIGURES	ii
LIST OF TABLES	ii
ACKNOWLEDGEMENTS	iii
1.0 SUMMARY	1
2.0 INTRODUCTION	2
3.0 TEST METHODS AND PROCEDURES	5
3.1 Equipment and Instrumentation	5
3.1.1 Vibration Test Platform	5
3.1.2 Test Fixtures and Test Seats	5
3.1.3 Instrumentation and Acceleration Measurement System	6
3.2 Vibration Test Signals	7
3.2.1 Type of Signal	7
3.2.2 Signal Duration, Frequency Range, Anti-Aliasing Filter, and Sampling Rate	9
3.3 Subjects	10
3.4 Test Matrix/Subject Test Log	10
3.5 Data Collection	11
4.0 DATA PROCESSING	12
4.1 R.M.S. Acceleration Spectra Characteristics	12
4.2 Transfer Functions	13
4.2.1 Single-Input/Single-Output Model	13
4.2.2 Multiple-Input/Single-Output Model	14
4.3 Overall Unweighted and Weighted Acceleration Levels	15
4.3.1 Overall Unweighted Acceleration Levels	16
4.3.2 Overall Weighted Acceleration Levels for Comfort and Health Risk Assessment	16
4.4 Percent (%) Vibration Reduction	18
5.0 DATA ANALYSIS	20
5.1 R.M.S. Acceleration Spectra	20
5.2 Transfer Functions	22
5.3 Peak Accelerations	23
5.4 Overall Unweighted Acceleration (1-80 Hz)	26
5.5 Discomfort and Health Risk Assessments (ISO 2631-1)	29
5.5.1 Comfort Reaction Comparison	29
5.5.2 Health Risk Comparison	30
6.0 REFERENCES	38
LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS	40

LIST OF FIGURES

Figure 1. H-60S Seat Mounted onto SIXMODE Platform. Sensor locations also shown.....	6
Figure 2. Acceleration Pads Attached to Seat Pan and Seat Back. Note routing of cables to lower back seat, then exiting at lower corner.	7
Figure 3. HH-60M Blackhawk Acceleration Spectra Regenerated on SIXMODE Platform.....	8
Figure 4. FLAT SPECTRUM Acceleration Spectra Regenerated on SIXMODE Platform	9
Figure 5. ISO 2631-1 Frequency Weightings W_d , W_k , and W_c	17
Figure 6. Health Guidance Caution Zone (ISO 2631-1, Annex B)	18
Figure 7. Sample R.M.S. Acceleration Spectra – FLAT SPECTRUM Exposure	21
Figure 8. Sample R.M.S. Acceleration Spectra – HH-60M AVSS ON Exposure	21
Figure 9. Sample Seat Pan Transfer Functions (Transmissibility)	22
Figure 10. Mean Unweighted BPF Peaks \pm One Standard Deviation	24
Figure 11. Mean Overall Unweighted Acceleration \pm One Standard Deviation	27
Figure 12. Mean Overall Weighted Accelerations, $pVTVs$, and $oVTVs \pm$ One Standard Deviation for Assessing ISO Comfort Reaction.....	30
Figure 13. Mean Overall Weighted Accelerations and Vector Sum	31
Figure 14. Exposure Duration Thresholds for Potential Health Risk	33

LIST OF TABLES

Table 1. Rotary-Wing/Tilt-Rotor Aircrew Vibration Studies Conducted by AFRL 711 HPW	3
Table 2. Example Test Matrix and Subject Test Log	11
Table 3. ISO 2631-1 Frequency Weightings and Multiplying Factors.....	17
Table 4. Unweighted BPF Peaks	25
Table 5. Percent (%) Unweighted BPF Peak Acceleration Reduction	26
Table 6. Overall Unweighted Accelerations.....	28
Table 7. Percent (%) Overall Unweighted Acceleration Reduction	29
Table 8. Overall Weighted Accelerations and Vector Sum.....	31
Table 9. Percent (%) Overall Weighted Acceleration and Vector Sum Reduction	32
Table 10. Exposure Duration Thresholds for Potential Health Risk, Threshold Difference, and Percent (%) Increase	34

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of the other team members who participated in the conduct of the recent (2022-2023) seat vibration mitigation proof-of-concept (PoC) studies. They are Mr. Max Grattan, Infoscitex, DCS and Mr. Michael Collier, Infoscitex, DCS. Their support in these efforts was instrumental in developing this seat vibration mitigation PoC methodology.

The views expressed are those of the author and do not reflect the official views of the United States Air Force, nor the Department of Defense (DoD). Mention of trade names, commercial products, or organizations do not imply endorsement by the U.S. Government.

1.0 SUMMARY

This document presents a military aircraft seat vibration mitigation PoC methodology and capability established within the Air Force Research Laboratory (AFRL) 711th Human Performance Wing (711 HPW) for human-occupied laboratory test/analysis of vibration mitigation seating system concepts. The methodology specifically targets military rotary-wing/tilt-rotor aircraft but can be extended to military fixed-wing propeller aircraft. It specifies the recommended facility and instrumentation requirements, test regime, and data collection/analysis processes and procedures and is packaged for quality, time, and cost effectiveness. The development of this PoC methodology leveraged the studies conducted by the AFRL 711 HPW. The first study was conducted in 2018 (Smith, S.D., et al., 2019) and is used to illustrate the analyses and presentation of results that have been explored in the development of the PoC methodology. The referenced report for this study has been cleared for public release. Three additional studies were conducted between 2021 and 2023. The studies included a pilot seat and cabin seat designed for use in a fixed-wing propeller aircraft, and a pilot seat designed for a helicopter. The reports for these studies have not been cleared for public release at this time. This document is intended as a user guide for military aircraft seat vibration mitigation PoC testing and analysis for improving seat design where further mitigation may be warranted prior to conducting expensive, disruptive, and time-consuming flight tests.

2.0 INTRODUCTION

Epidemiological surveys conducted over the years have consistently reported that low back pain is a prevalent health risk among military aviators, particularly those aircrew who fly rotary-wing aircraft. Both ‘transient’ back pain lasting for short durations and ‘chronic’ back pain that persists over time have been shown to be higher in these helicopter aircrews (Bongers, et al., 2007). Studies have revealed that aircrew of rotary-wing aircraft have a greater risk of spinal disease such as disc herniation (Hermes, E.D., et al., 2010), particularly of the lumbar spine (Knox, et al. 2018). A 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 T&E) found that ~85 percent (%) of the rotary-wing aircrew surveyed have suffered back, leg, or neck pain associated with flying helicopters (Hamon, K., et al, 2012). Poor posture, inadequate seats, and aircraft vibration were targeted as contributing factors, although their synergies and physiological mechanisms are unknown. The BCA (Hamon, K., et al, 2012), as well as previous surveys, emphasized that musculoskeletal pain and discomfort in these aircrew have a significant negative impact on mission effectiveness.

The persistent vibration generated by rotary-wing aircraft is attributed to the propulsion system. The propeller rotation frequency (PRF), also known as the rotor speed, occurs at a relatively low frequency that is typically below 10 Hertz (Hz). Additional vibration peaks are generated at multiples of the PRF, in particular, at the blade passage frequency (BPF), which is the number of main rotor blades times the PRF. The BPF typically occurs between 10 and 20 Hz in these aircraft. Substantial vibration can also be generated at multiples of the BPF. The AFRL, 711 HPW, Wright-Patterson AFB, OH, has conducted several studies to characterize the vibration transmitted to the military occupants during flight operations aboard rotary-wing/tilt-rotor platforms. These field studies were conducted on the aircraft platforms listed in Table 1. The studies have shown that the most prevalent vibration associated with these aircraft and typically transmitted to the occupant occurs at the BPF and beyond.

Low frequency vibration (below 10 Hz) is common in the operation of heavy ground vehicles, including those used in agriculture, excavation, transport (trucks, trains, and buses) and for off-road purposes including military operations. Whole-body resonance in the human body is known to occur between 4 and 8 Hz during seated vertical vibration. In this frequency range, large relative motions occur between the upper and lower torso that are transmitted to the head. It is easy to envision how these relative motions at low frequencies could lead to back discomfort, pain, and even injury from a biomechanics perspective. Vibration transmission to the upper torso and head decreases at frequencies beyond 10 Hz, unless the exposures are of substantial amplitudes, or the occupant is in contact with a vibrating seat back or headrest (Smith, et al., 2007). The evaluations that have been conducted during military aircraft operations have shown very low levels of vibration transmission to the seated occupant below 10 Hz in the vicinity of the PRF. The highest vibration levels have been primarily observed in the vicinity of the BPF and at multiples of the BPF. The higher frequencies can be felt and are primarily perceived at the interfaces where the body is in contact with the vibrating surface, including the upper legs, buttocks, and back, as indicated in laboratory studies (Smith, S.D.,

Table 1. Rotary-Wing/Tilt-Rotor Aircrew Vibration Studies Conducted by AFRL 711 HPW

AIRCRAFT	OWNER	LOCATION	FLIGHT DATE
AH-1Z SuperCobra	USMC	PAX River NAS, MD	9-11 Mar 2005
CH-47F Chinook	MD ANG	Aberdeen Proving Ground, MD	19 Oct 2017
CV-22 (1) Osprey	413 FLTS	Hurlburt Field, FL	14 Jun 2007
CV-22 (2) Osprey	20 th SOS	Cannon AFB, NM	22 Jun 2022
MH-65D Dolphin	USCG auto	Cecil Field, FL	18 Sep 2018
HH-60M Blackhawk	VT ANG	South Burlington, VT	25-26 Sep 2013
UH-1N Iroquois	413 FLTS	Duke Field, Eglin AFB, FL	26 Sep 2018
UH-60L Blackhawk	MD ANG	Aberdeen Proving Ground, MD	17 Oct 2017
UH-72 Lakota	VT ANG	South Burlington, VT	23-24 Sep 2013
ANG - Army National Guard FLTS - Flight Test Squadron HITRON - Helicopter Interdiction Tactical Squadron NAS - Naval Air Station SOS – Special Operations Squadron USCG - United States Coast Guard USMC - United States Marine Corp			

2008) and in the survey results from the field study conducted on the HH-60M (Smith, S.D., et al., 2014).

There are guidelines that can be applied to assess the discomfort and health risk associated with occupational vibration exposures (International Organization for Standardization, ISO-2631-1:1997; DoD, Military Standard (MIL-STD) 1472H; and the American Conference of Governmental Industrial Hygienist (ACGIH), Whole Body Vibration (WBV) Threshold Limit Value (TLV)). These guidelines focus on vibration exposures in the frequency range 0.5 to 80 Hz that are transmitted to the occupant in direct contact with a support surface, such as a seat. The guidelines were applied to the studies listed in Table 1. The results strongly suggested that aircrew occupational exposures to vibration generated by rotary-wing aircraft do cause discomfort and present the potential for health risk. For example, level flight aboard the AH-1Z SuperCobra (Smith, S. D., 2005) exposed the aircrew to the potential for health risk in as little as 2 to 3 hours of daily flight, with the average at approximately 8 hours. Onboard the UH-60L Blackhawk during level flight (Smith, S.D., et al., 2019), the pilot and aft aircrew were exposed to the potential for health risk in 4 hours or less during daily flight. Onboard the CH-47F Chinook (Smith, S.D. and Chervak, S.G., 2020a) and the MH-65D (Smith, S.D. and Chervak, S.G., 2019) most aircrew were exposed to potential health risk in less than 8 hours of daily flight, with some exposures presenting risk in as little as 1 to 2 hours of daily flight. Onboard the Air

Force CV-22 during level flight (Smith, S.D. et al, 2008; Smith, S.D., 2023), the potential health risk thresholds were more variable but as low as 2 hours of daily flight. The results of the studies addressing aircrew vibration levels and health risk (Table 1), and the prevalence of low back pain reported among these aircrew, strongly support the development of technologies that can mitigate vibration associated with aviator occupational health risk.

One approach to mitigating the transmission of vibration to aircrew is to focus on those surfaces and structures that directly support the seated aviator, i.e., the seating system. The DoD has funded the development of new military aircraft seat technologies for the effective mitigation of operational vibration transmitted to the aircrew. The Naval Air Systems Command (NAVAIR) has been a lead in the development of seat vibration mitigation concepts that targeted specific military rotary-wing and fixed-wing platforms. The AFRL 711 HPW has supported these efforts by conducting in house human vibration laboratory testing and evaluation of these seat concepts. Gauging the reduction in vibration transmission and assessing the effective improvement of comfort and health risk associated with these prototype seating systems required the development and implementation of appropriate test and analysis procedures that specifically targeted military operations. It is imperative that formal laboratory PoC studies are conducted to address the extent to which any prototype system meets the design requirements. These studies can also be used to identify any design shortcomings and provide key information for quick turn-around design improvements. This is extremely advantageous to the military prior to conducting expensive, limited, and time-consuming flight tests.

This document presents a military aircraft seat vibration mitigation PoC methodology and capability established within the AFRL 711 HPW for human-occupied laboratory test/analysis of vibration mitigation seating system concepts. The methodology specifically targets military rotary-wing/tilt-rotor aircraft but may be applied to fixed-wing propeller aircraft. It specifies the recommended facility and instrumentation requirements, test regime, and data collection/analysis processes and procedures and is packaged for quality, time, and cost effectiveness. The development of this PoC methodology leveraged the studies conducted by the AFRL 711 HPW. The first study was conducted in 2018 (Smith, S.D., et al., 2019) and is used to illustrate the analyses and presentation of results that have been explored in the development of the PoC methodology. The referenced report for this study has been cleared for public release. Three additional studies were conducted between 2021 and 2023. The studies included a pilot seat and cabin seat designed for use in a fixed-wing propeller aircraft, and a pilot seat designed for a helicopter. The reports for these studies have not been cleared for public release at this time. This document is intended as a user guide for military aircraft seat vibration mitigation PoC testing and analysis prior to flight test.

3.0 TEST METHODS AND PROCEDURES

3.1 Equipment and Instrumentation

3.1.1 Vibration Test Platform

A human-rated vibration system, capable of generating simultaneous vibration in the three orthogonal directions, fore-and-aft (X), lateral (Y), and vertical (Z), is required to conduct the PoC tests. The human rating should be in accordance with the performing organization's policies. There should be approved operation and maintenance procedures and checklists in place to assure subject safety, including both manual and electronic limits that immediately stop platform movement and/or shut down the system if exceeded. An emergency plan should be in place to remove the subject from the facility in case the subject becomes ill or injured during the test. The minimum frequency range of interest for human exposure to vibration is 0.5 to 80 Hz, in accordance with the ISO 2631-1. The system should be capable of regenerating vibration that represents the acceleration amplitudes and frequency components of the operational exposure(s) associated with the targeted aircraft. These exposures may include key frequency components that occur beyond 80 Hz. It is advantageous to include these frequency components in the exposures and data collection/processing scheme, where feasible. Section 3.2 provides guidelines on the frequency range, anti-aliasing, and sampling rate. The vibration system must be capable of generating these signals with a payload representing the seating system, any ancillary equipment required to mount and secure the seat to the platform, and the human (max human weight of ~114 kilograms(kgs) or ~251 pounds (lbs)).

3.1.2 Test Fixtures and Test Seats

The methodology presented in this guideline requires the comparison of vibration response characteristics between the prototype seat configuration and the original seat configuration used in the aircraft. This may include the testing of two different seats or could include the original seat that is modified with a vibration isolation system or device. The vibration mitigation/isolation system may be passive, semi-active, or active. If there are two different seats, it is assumed that both will be attached similarly in the targeted aircraft. A special test fixture will most likely be required to attach the original and prototype seats to the platform. Figure 1 illustrates a UH-60S seat attached to the human-rated Six Degree-of-Freedom Motion Simulator (SIXMODE) located at AFRL 711 HPW (Smith, S.D., et al. 2019). The test fixture would be considered to include the black mounting plate with attached rails. This configuration would be used for both the prototype and original seat. In addition, if the prototype includes a redesign of the mounting structure, which may require a different test fixture, then additional data may need to be collected if the goal is to delineate the contribution of the mounting structure vs the seat itself. If the original seat is modified, it may be possible to remove or disable the vibration isolation system or device, in order to test the original seat. All tested seat configurations should include, at a minimum, a subject lap belt. A shoulder harness is also recommended.

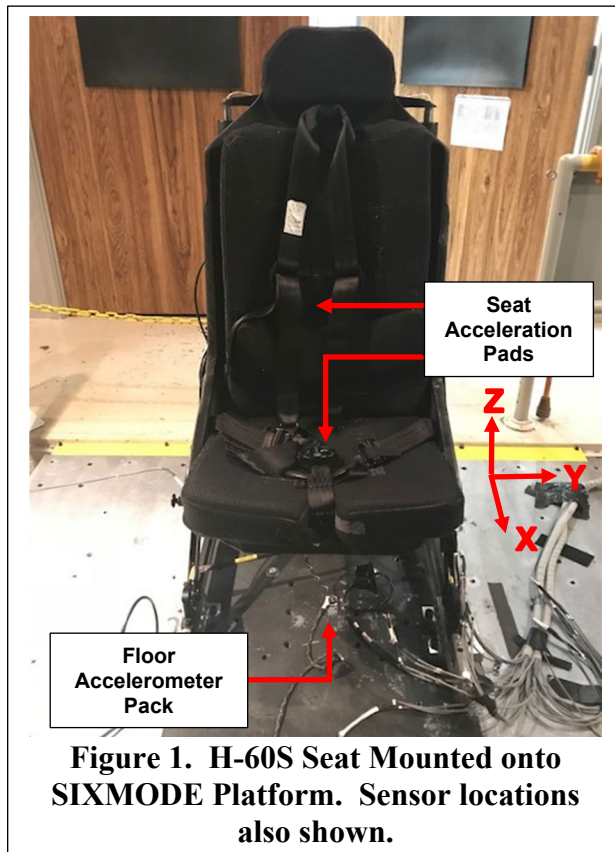


Figure 1. H-60S Seat Mounted onto SIXMODE Platform. Sensor locations also shown.

3.1.3 Instrumentation and Acceleration Measurement System

At a minimum, there are two measurement sites required to assess the vibration transmitted to the seated occupant. First, triaxial acceleration measurements should be made to quantify the input vibration to the seating system. Second, triaxial measurements should be made to characterize the vibration transmitted to the human occupant by the supporting seat structure, i.e., at the interface between the seat surface or seat pan (on top of any cushion) and the human occupant. In addition, triaxial accelerations may be collected on the underside of the seat pan (if rigid) and at the interface between the seat back (on top of any cushion) and occupant. The measurement on the underside of the seat pan may provide insight as to any effects of the seat pan cushioning materials at the interface. The triaxial accelerations measured at the seat/occupant interfaces require the use of a sensor(s) embedded within a flexible pad in order to minimize the influence of the sensor(s) on the structural characteristics of any seating material, and to ensure a sufficient contact surface for the seated occupant. It is emphasized that these pads should be placed on top of any seat cushioning material and have direct contact with the occupant's buttocks. The seat pan pad should be configured beneath the ischial tuberosities to obtain the best pressure distribution. The seat back pad should be configured where the occupant's back has the greatest contact with the seat. Double-sided adhesive tape and duct tape provide a good method for attaching and stabilizing the pads to the seat/seat cushion surface. It is recommended that the sensor cables from the pads be routed to the back lower edge of the seat and out at the lower back corner (tucked between the seat pan and seat back cushions, if possible). The seat/occupant interface accelerations will be used to assess comfort and health risk associated with the measurement in accordance with ISO 2631-1. ISO 2631-1 references ISO 10326-1 regarding the

design of the seat pad. Figure 1 shows the location of the acceleration pads on the seat. Figure 2 illustrates the attachment of these pads to the seat pan and seat back and the routing of cables in a UH-60L Blackhawk seat (Smith, S.D., et al., 2019). The triaxial coordinate system is relative to the seated occupant and illustrated in Figure 1. The coordinate system should follow the guidelines of ISO 2631-1. The three axes or directions include fore-and-aft (X), lateral (Y), and vertical (Z) as illustrated in Figure 1.

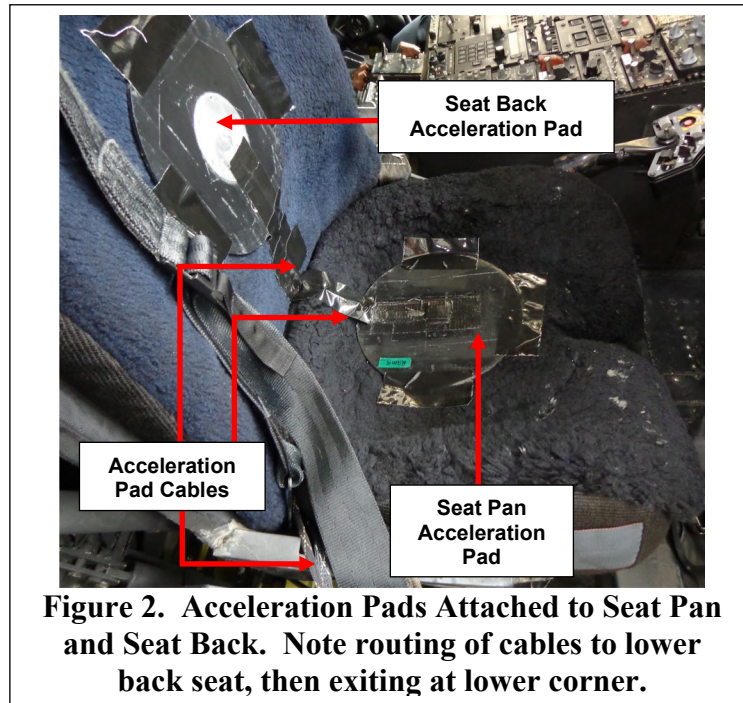


Figure 2. Acceleration Pads Attached to Seat Pan and Seat Back. Note routing of cables to lower back seat, then exiting at lower corner.

Other sensor locations may be desirable for a more detailed analysis, as mentioned in Section 3.1.2. While sensors can be placed on the subject, i.e., subject head or helmet, this may require approval of a human protocol by an Institutional Review Board (IRB) (see Section 3.3). All sensor cables are routed to a designated acceleration measurement system or data acquisition system (DAS) capable of collecting data in accordance with the guidelines and recommendations presented in Section 3.5. Data channels are defined in the DAS and correspond to a specific measurement site and direction. At a minimum, there should be six (6) data channels (platform floor X, Y, and Z, and seat pan interface X, Y, and Z).

3.2 Vibration Test Signals

3.2.1 Type of Signal

There are two types of vibration test signals defined by this PoC methodology. The first type of signal is representative of the vibration occurring in the targeted aircraft and transmitted to the seating system and occupant. As mentioned in the Introduction, rotary-wing and fixed-wing propeller aircraft generate vibration at relatively discrete frequencies associated with the propulsion system. The frequency components are typically the target for vibration mitigation/isolation. Rotary-wing aircraft and fixed-wing propeller aircraft tend to generate substantial vibration in all three axes. For rotary-wing/tilt-rotor aircraft, the PRF typically occurs

below 10 Hz. The BPF typically occurs below 20 Hz. The PRF and BPF associated with fixed-wing propeller aircraft typically occur at higher frequencies as compared to military rotary-wing/tilt-rotor aircraft. The PRF for many military fixed-wing propeller aircraft is above 10 Hz (C-130 variants; E-2C, E-2D). Depending on the number of blades, the BPF can be above 100 Hz. Figure 3 illustrates the acceleration spectra associated with level flight aboard the HH-60M Blackhawk that was recreated on the SIXMODE platform. For this aircraft variant, the figure shows the BPF peak occurring in all three axes at 17.0 Hz. It is noted that the highest BPF peak

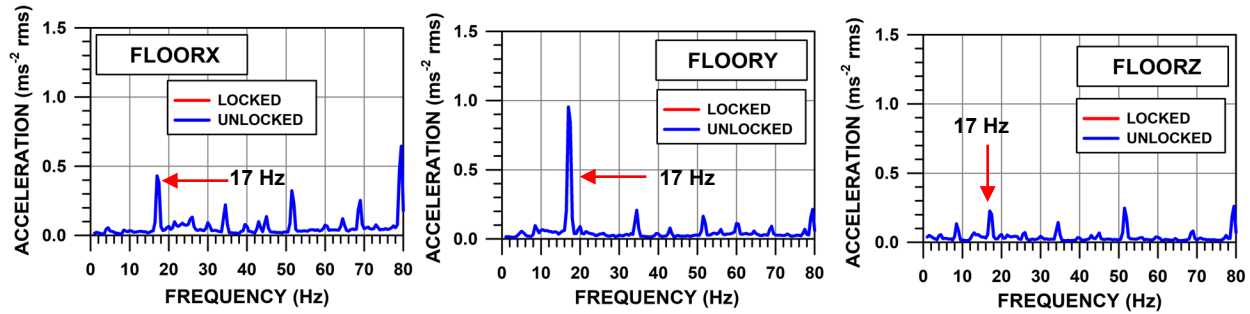


Figure 3. HH-60M Blackhawk Acceleration Spectra Regenerated on SIXMODE Platform

occurs in the lateral (Y) direction. For the PoC tests, it is recommended that the signal represent a flight test condition that the aircrew are most likely to be exposed to for the longest duration during their daily mission. It is expected that this would include level flight. If there are known conditions that are of particular concern, this may warrant inclusion in the test matrix. It is expected that the frequency locations of the highest accelerations will be similar but most likely of different amplitudes. This does depend on the particular aircraft and whether the rotor operates at the same revolutions-per-minute (RPM) for the targeted maneuvers.

There are software packages that can recreate multi-axis acceleration time histories onto a vibration platform. Acceleration time histories collected during flight were recreated in the AFRL 711 HPW SIXMODE facility using the Iterative Control System (ICS) software (Servotest Testing Systems LTD, Egham Surrey, England). There is a locally-developed procedure (LDP) or operating instruction (OI) entitled “SIXMODE ICS Steps for Recreating Vibration Signals on the SIXMODE (WPRHBF-15) that provides guidance on this process. If only spectral components associated with the specific aircraft are known, there are other methods, such as sum-of-sines, that can be used to create a time history with the targeted frequency components of interest. The time history should include simultaneous vibration in all three axes or directions.

The second type of signal is the FLAT SPECTRUM vibration signal that is characterized by constant acceleration energy distributed across all frequency components within a specified frequency range, thus producing the ‘flat’ appearance. The FLAT SPECTRUM signal allows for the general assessment of the vibration mitigation/isolation effectiveness across a broader frequency range. The responses to the FLAT SPECTRUM are used to estimate the multi-axis transfer functions or transmissibilities between the input vibration at the table floor and the seat/occupant interfaces described in Section 4.2. Figure 4 illustrates the acceleration spectra associated with the FLAT SPECTRUM used in the AFRL SIXMODE facility. The FLAT SPECTRUM was created using the sum-of-sines approach between 1 and 80 Hz to include the frequency range of interest with regard to human vibration exposure. Unfortunately, the FLAT

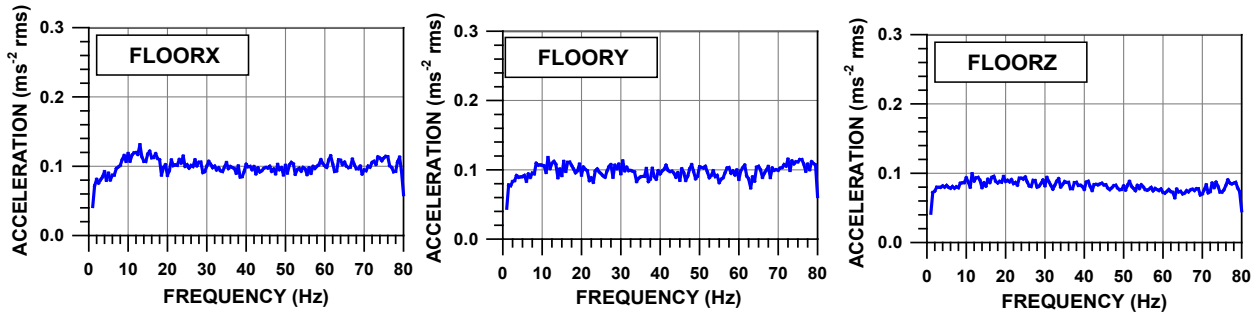


Figure 4. FLAT SPECTRUM Acceleration Spectra Regenerated on SIXMODE Platform

SPECTRUM does not provide the ability to evaluate seat transfer functions at frequencies associated with the BPF of some military fixed-wing propeller aircraft. A white noise signal defined within the appropriate frequency range and containing sufficient acceleration energy at each frequency component, could be used. While transfer functions can be generated using the aircraft exposure, caution must be taken when interpreting the vibration transmission at frequencies associated with very low or no acceleration energy, as shown in Figure 3 for the HH-60M. The low input may be at levels associated with the noise floor of the vibration platform and most likely will be associated with low coherence. In addition, it is expected that the occupant/seat system is nonlinear, i.e., the interface frequency response varies depending on the amplitude of the input vibration.

Vibration data collected on the aircraft platforms listed in Table 1 are available in the AFRL 711 HPW Collaborative Biomechanics Data Network (CBDN). The one exception is the AH-1Z SuperCobra since the associated technical report is currently Distribution B, authorized to US Government agencies only. Work is underway to clear the document for public release. The CBDN is available to all DoD employees and their contractors who have an active DoD Computer Access Card (CAC). For each platform, the acceleration time histories, constant bandwidth root-mean-square (R.M.S.) accelerations, and one-third octave proportional bandwidth R.M.S. accelerations are tabulated for each data record. Each data record is associated with a flight condition and includes multiple channels of acceleration data. At a minimum, data are available at the seat pan and seat back interfaces, and the floor or other rigid structure associated with the seating system. These data can, and have been used, to recreate field or operational data for conducting research and for testing seating systems in accordance with this PoC methodology.

3.2.2 Signal Duration, Frequency Range, Anti-Aliasing Filter, and Sampling Rate

The duration of the exposure signal will depend on the characteristics of the field signal being recreated. If the field signal is quite long, it may be advantageous to extract a representative section to recreate in the laboratory. It is cautioned that the signal should be evaluated for consistency when selecting a representative section. The vibration characteristics occurring during level flight are expected to be relatively consistent over time, unless perturbations occur, most likely due to weather. Field data collected by the 711 HPW are typically 20-s records for a specified flight condition or maneuver. Multiple records are collected for the flight condition to gauge the range of vibration levels. The selected 20-s record is then recreated for the PoC study but can be repeated as long as necessary for data collection.

As mentioned in Section 3.1.1, the ISO 2631-1 calls for the assessment of health risk in the frequency range of 0.5 Hz to 80 Hz. A range of 1.0 to 80 Hz can be used if vibration below 1 Hz is considered inconsequential. When collecting field or operational vibration data, the ISO 2631-1 recommends that a low-pass filter (-3 decibels (dB)) be applied to the signal that is at least 1.5 times the highest frequency of interest. It is recommended that the sampling rate be greater than twice the frequency of the low pass filter so that the low-pass filter (anti-aliasing) is below the Nyquist frequency. A typical low-pass filter is the 6-pole Butterworth filter. As an example, if 120 Hz is the highest frequency of interest, the low-pass filter should be at least 180 Hz, and the sampling rate should be greater than 360 samples per second. It is recommended that higher sampling rates be considered when both collecting field or operational data and recreating the signal to ensure good estimations of the peak values. Field signals can also be interpolated (MATLAB[®] Signal Processing Toolbox) to obtain a more desirable sampling rate for laboratory use. The AFRL 711 HPW applies a 250 Hz low-pass filter and digitizes field signals at 1024 samples per second for evaluating human vibration exposure in the field. These same values are used when recreating the signal for laboratory studies.

3.3 Subjects

This PoC methodology requires the use of human volunteer subjects that will be exposed to whole-body vibration. Depending on the organization conducting the tests, this may require approval for human use by an IRB. The recent PoC tests conducted at the 711 HPW were approved as “not human subject research” (NHSR) by the AFRL IRB. The studies were considered non-generalizable test and evaluation. Only the targeted seating system and SIXMODE platform were instrumented. No data were collected directly from the subject. There may be other requirements set forth by the performing organization, in addition to those mentioned in Section 3.1.1 when conducting human vibration studies including approved test plans, technical review board (TRB) approval, and safety review board (SRB) approval. The subjects should be in good health with no history of musculoskeletal injury or pain, particularly of the head/neck/back. They should also have no history of motion sickness or vertigo. A minimum of five (5) male and/or female subjects are recommended for these studies. It is advisable that each subject be briefly exposed to the test signals prior to formal testing and data collection. Subjects should wear similar clothing for each test required by the study.

3.4 Test Matrix/Subject Test Log

A test matrix and/or subject test log should be established for the study. Table 2 illustrates an example. In this particular case, SEATA is the original aircraft seat and SEATB is the prototype seat. Each seat configuration is associated with a test session. For the example test log depicted in Table 2, there are two exposure signals representing the aircraft vibration in addition to the FLAT SPECTRUM. At least one (1) run/record must be collected for each exposure. Each test session may be conducted on the same day or on different days, depending on the time required for reconfiguration. Typically, all subjects would complete Test Session 1 before proceeding to Test Session 2.

Table 2. Example Test Matrix and Subject Test Log

STUDY TITLE			
Test #:		Subject ID:	
Test ID:			
Subject Wt (lbs):		Subject Ht (in):	
TEST SESSION 1			
SEAT CONFIGURATION	EXPOSURE	RUN/RECORD #	√
SEATA (Original)	SIGNAL1	1	
	SIGNAL2	2	
	FLAT	3	
TEST SESSION 2			
SEAT CONFIGURATION	EXPOSURE	RUN/RECORD #	√
SEATB (Prototype)	SIGNAL1	1	
	SIGNAL2	2	
	FLAT	3	

3.5 Data Collection

During each exposure and each run/record identified in the test matrix, acceleration time histories should be collected simultaneously in all three axes for all targeted measurement sites. It is recommended that the data collection sampling rate equal the sampling rate of the recreated signal, after applying a low-pass filter (see Section 3.2.2). The length of the run/record should be selected to ensure representation of the signal that was recreated. For example, if the recreated signal is 20 s in length, then the collected record should at least be 20 s in length. A longer collected record may be desirable. It may also be desirable to collect more than one record for each exposure.

4.0 DATA PROCESSING

The time histories from each channel of data are used to generate several metrics that may be used for comparing the vibration transmission characteristics of the tested seat configurations and for evaluating the vibration mitigation performance of the prototype seat. The AFRL 711 HPW has developed a MATLAB[®] script called AnalyzeVib2005.m that includes the calculation of both the constant bandwidth and one-third octave bandwidth acceleration spectra (using a script developed by Couvreur, 1997) as described in Section 4.1, as well as the calculation of the transfer functions for both models described in Section 4.2. For each data record, a MATLAB[®] app is first applied to assemble a table of all data channel time histories. AnalyzeVib2005.m imports the table for each data record and generates the requested metrics. AnalyzeVib2005.m is restricted to data sampled at 1024 samples per second. A description of the processing/calculation of the recommended metrics and how they can be used in the seat performance analysis are described below.

4.1 R.M.S. Acceleration Spectra Characteristics

The R.M.S. acceleration spectra provide insight into the major frequency components and associated amplitudes in each axis or direction at each measurement site. The spectra provide key information for developing the most effective vibration mitigation strategies for the particular environment. These spectra are generated by applying digital processing techniques to each data channel included in the data record. Typically, the power or auto spectral density (PSD) is first estimated in constant frequency bandwidths in units of ms^{-2}/Hz . Several signal processing methods are available for estimating the PSD, depending on the software package. For example, the AFRL 711 HPW uses the MATLAB[®] Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) and Welch's Method (Welch, P. D., 1967) to process the constant-bandwidth spectra (via AnalyzeVib2005.m). Each channel time history included in the data record is divided into two-second sub-segments with a 50% overlap. A Hamming window is applied to each sub-segment and the resultant power spectral densities averaged over the record duration. This generates the PSD in 0.5 Hz increments. The R.M.S. acceleration spectrum is then generated from the PSD for each data channel included in the data record by multiplying the PSD by the frequency bandwidth (0.5 Hz) and taking the square root of the resultant for each frequency component. Figures 3 and 4 illustrate examples of the R.M.S. acceleration spectra. The units of the R.M.S. acceleration are ms^{-2} rms. The frequency range is limited by the Nyquist frequency (one half the sampling rate). As mentioned, for human vibration analysis, the frequency range of interest is between 0.5 Hz (or 1.0 Hz if applicable) and 80 Hz. It may be advantageous to generate the spectra beyond 80 Hz, particularly in the case where the aircraft may generate a BPF that is beyond 80 Hz, or to gauge any substantial amplitudes at multiples of the BPF that may be perceived by the occupant (see Section 3.2.2).

It may be a tedious process to compare the R.M.S. spectra between the seat configurations among the subjects. The main objective is to confirm the similarity in the frequency location of the peak responses and to identify any obvious differences in the amplitude of peak responses and frequency distribution between seat configurations. The distinct acceleration peaks generated by rotary-wing/tilt-rotor aircraft, specifically those peaks that may have been specifically targeted for mitigation in the design of the prototype, may warrant it advantageous to extract these peaks

and compare their amplitude between seat configurations. The R.M.S. spectra, either constant bandwidth data or proportional bandwidth data, can be used to calculate the overall unweighted and weighted acceleration levels associated with exposure to the aircraft signal(s) (Section 4.3).

4.2 Transfer Functions

The effective mitigation of vibration transmission to the seated occupant can be objectively gauged by applying engineering processes. These processes characterize a numerical relationship, known as the transfer function, between the source of vibration input and the excited system, in this case, the seated occupant. There are several ways to calculate a ‘transfer function’ from simple output-input ratios to more complex mathematical expressions. The transfer functions described in this document are frequency dependent and use the cross-spectral density method applied to the FLAT SPECTRUM time history data to quantify the linear relationship between the output vibration at the seat/occupant interface and input vibration at the platform floor. This complex ratio is typically used to describe the behavior in terms of the amplitude (typically called the transmissibility) and phase occurring across the frequency range of interest between the output and input accelerations. In addition, it is important to consider the coherence, a frequency-dependent value between 0 and 1 that reflects the extent of the linear relationship between the output and input. Noise and other sources unrelated to the input vibration that affect the output can reduce the coherence. This is a concern if the transfer function is calculated based on the aircraft vibration. At frequencies where the acceleration is quite low, contributions from noise and other sources may further complicate the analysis as described in Section 3.2.1.

Two models that use the cross-spectral density method are described. The first model considers a single-axis input at the floor and a single-axis output at the seat/occupant interface without considering any linear contribution from the other input orthogonal axes to the targeted output. The second model considers a multi-axis input at the floor, and each single-axis output at the interface. This model does take into account the linear contribution from the other orthogonal input axes to the targeted output. The MATLAB[®] Signal Processing Toolbox can be used to estimate the transfer functions associated with the input at the platform floor and the output at the subject/seat interfaces. The following summarizes the mathematical equations associated with each model. As mentioned in Section 4.0, the AFRL 711 HPW MATLAB[®] script AnalyzeVib2005 includes provisions for calculating the transfer functions for the two models described above.

4.2.1 Single-Input/Single-Output Model

The equation for calculating the single-input/single-output transfer function for input i ($i = x, y, z$) and output O ($O = X, Y, Z$) is defined as:

$$H_{iO}(w) = S_{iO}(w)/S_{ii}(w) \quad (1)$$

where

- $H_{iO}(w)$ = Complex transfer function for input i and output O ,
- $S_{iO}(w)$ = Cross-spectrum for input i and output O ,
- $S_{ii}(w)$ = Auto-spectrum for input i .

The equation for calculating the ordinary coherence is:

$$C_{iO}(w) = |S_{iO}(w)|^2 / S_{ii}(w)S_{OO}(w) \quad (2)$$

where

- $C_{iO}(w)$ = Ordinary coherence between input i and output O ,
- $|S_{iO}(w)|$ = Absolute value of cross-spectrum between input i and output O ,
- $S_{ii}(w)$ = Auto-spectrum for input i ,
- $S_{OO}(w)$ = Auto-spectrum for output O .

With three inputs and three outputs there are a total of nine (9) transfer functions and (9) associated ordinary coherences. The transfer function amplitude (transmissibility) and phase can be extracted from the complex values for plotting and analysis.

4.2.2 Multiple-Input/Single-Output Model

The system transfer matrix for calculating the multiple (three)-input/single-output transfer functions (Bendat, J.S. and Piersol A.G., 1993; Newland D.E., 1984; Naidu P.S., 1996) is defined as:

$$\begin{bmatrix} H_{xO} \\ H_{yO} \\ H_{zO} \end{bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{xO} \\ S_{yO} \\ S_{zO} \end{bmatrix} \quad (3)$$

where

- H_{xO}, H_{yO}, H_{zO} = Complex transfer functions for the three inputs x, y, and z and single output O ,
- S_{xx}, S_{yy}, S_{zz} = Auto-spectrum of the respective inputs,
- $S_{xy}, S_{xz}, S_{yz}, S_{yx}, S_{zx}, S_{zy}$ = Cross-spectrum between the respective inputs.

The partial coherence associated with H_{xO} is:

$$C_{xO|yz}^2 = \left[(1 - C_{x.yz,O.yz}^2) C_{xO}^2 \right] / \left[(1 - C_{x.yz}^2)(1 - C_{O.yz}^2) \right]. \quad (4)$$

where

- C_{xO}^2 = Ordinary coherence between the x input and O output (Equation (2)),
- $C_{xO|yz}^2$ = Value between 0 and 1 that reflects the extent to which the output O is linearly related to the input x after removing the contributions of the inputs y and z,
- $C_{x.yz,Z.yz}^2$ = Fraction of the common power in the x input and the O output that is caused by the y and z inputs.

The partial coherence associated with H_{yO} is:

$$C_{yO|xz}^2 = \left[(1 - C_{y.xz,O.xz}^2) C_{yO}^2 \right] / \left[(1 - C_{y.xz}^2)(1 - C_{O.xz}^2) \right]. \quad (5)$$

The partial coherence associated with H_{zO} is:

$$C_{zO|xy}^2 = \left[(1 - C_{z.xy,0.xy}^2) C_{zO}^2 \right] / \left[(1 - C_{z.xy}^2)(1 - C_{0.xy}^2) \right]. \quad (6)$$

The equations associated with $C_{0.yz}^2$, $C_{x.yz}^2$, and $C_{x.yz,0.yz}^2$ in Equation (4) are defined as:

$$C_{0.yz}^2 = \left\{ \begin{bmatrix} S_{Oy} \\ S_{Oz} \end{bmatrix}^T \begin{bmatrix} S_{yy} & S_{yz} \\ S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{yO} \\ S_{zO} \end{bmatrix} \right\} / S_{OO} \quad (7)$$

$$C_{x.yz}^2 = \left\{ \begin{bmatrix} S_{xy} \\ S_{xz} \end{bmatrix}^T \begin{bmatrix} S_{yy} & S_{yz} \\ S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{yx} \\ S_{zx} \end{bmatrix} \right\} / S_{xx} \quad (8)$$

$$C_{x.yz,z.yz}^2 = \left\{ \begin{bmatrix} S_{xy} \\ S_{xz} \end{bmatrix}^T \begin{bmatrix} S_{yy} & S_{yz} \\ S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{yO} \\ S_{zO} \end{bmatrix} \right\} / S_{xO} \quad (9)$$

Equations (7), (8), and (9) can be used in Equations (5) and (6) for calculating the partial coherences associated with H_{yO} and H_{zO} by substituting in the appropriate input y or z.

As with the single-input/single-output model, there are nine (9) transfer functions and nine (9) partial coherences.

The multiple coherence for output O is defined as:

$$C_{0.xyz}^2 = \left\{ \begin{bmatrix} S_{Ox} \\ S_{Oy} \\ S_{Oz} \end{bmatrix}^T \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{xO} \\ S_{yO} \\ S_{zO} \end{bmatrix} \right\} / S_{OO} \quad (10)$$

The multiple coherence reflects the extent to which all known inputs linearly contribute to a single output. There are three (3) multiple coherences per output, one associated with each input.

4.3 Overall Unweighted and Weighted Acceleration Levels

The overall unweighted and weighted acceleration levels in each of the three orthogonal axes or directions at each measurement site can be calculated in either the time domain or frequency domain. If calculated in the time domain, it is important to apply band-limiting filters to limit the overall values to the frequency range of interest. This will typically be the frequency range of 0.5 or 1.0 Hz to 80 Hz, since this is the frequency range of interest with regard to human vibration. The ISO 2631-1 recommends two-pole high-pass and low-pass filters with Butterworth characteristics at 0.4 Hz and 100 Hz respectively. As mentioned in Section 4.1, if the aircraft generates a substantial BPF peak that is beyond 80 Hz that is of concern for the aircrew, then a higher frequency low-pass filter may be in order (120 Hz). Both the overall unweighted and

weighted acceleration levels can also be calculated in the frequency domain using the constant bandwidth R.M.S. acceleration spectra or using the one-third octave proportional bandwidth R.M.S. acceleration spectra described in Section 4.1.

4.3.1 Overall Unweighted Acceleration Levels

In the frequency domain, the overall unweighted acceleration, a_l , is calculated as:

$$a_l = [\sum_i a_{li}^2]^{\frac{1}{2}} \quad (11)$$

where a_{li} is the unweighted R.M.S. acceleration associated with an axis or direction l (x, y, z) for the i th frequency component in m/s^2 . At a minimum, the overall unweighted acceleration levels should be calculated at the platform floor and occupant/seat pan interface. It is emphasized that the overall unweighted acceleration levels reflects the actual overall exposure that is not modified by the frequency weightings and multiplying factors used to assess comfort and health risk, as described below. Higher frequency components, particularly those that may be multiples of the BPF will contribute 100% to the overall levels.

4.3.2 Overall Weighted Acceleration Levels for Comfort and Health Risk Assessment

This PoC methodology includes a comparison of the seat configurations with respect to comfort and health risk. The assessments follow the guidelines provided in the ISO 2631-1, the ACGIH WBV TLV, and the MIL-STD 1472H. The use of these assessments in the PoC methodology helps gauge the effect of the particular vibration mitigation design on comfort and health risk. The frequency weightings (W) and multiplying factors (k) listed in Table 3 and used in the assessments are based on human sensitivity to the location, frequency, and direction of vibration. Figure 5 illustrates the ISO 2631-1 frequency weightings W_d , W_k , and W_c , and how they influence the contribution of the specific frequency components to the overall levels. As shown in the figure, unlike the overall unweighted vibration level, higher frequency components contribute substantially less to the overall weighted vibration level depending on the axis or direction.

In the frequency domain, the overall weighted acceleration, a_{wl} , in m/s^2 is calculated as:

$$a_{wl} = k_l [\sum_i W_{li}^2 a_{li}^2]^{\frac{1}{2}} \quad (12)$$

where W_{li} is the frequency weighting associated with direction l for the specific measurement site (seat pan or seat back) for the i th frequency component, and k_l is the multiplying factor for direction l and the particular assessment (comfort, health risk). If using constant bandwidth acceleration spectra, ISO 2631-1, Annex A, provides the mathematical equations for the frequency weightings. If using one-third octave proportional bandwidth acceleration spectra, the ISO 2631-1 lists the frequency weightings in tables. At a minimum, the overall weighted acceleration levels should be calculated at the seat pan interface site, but may include the seat back interface site (for comfort assessment).

For assessing comfort reaction, the point vibration total value (pVTV) is calculated at both the seat pan and seat back as the vector sum of the weighted fore-and-aft, lateral, and vertical accelerations after applying the appropriate multiplying factors for the measurement location (seat pan or seat back):

$$pVTV = [a_{wx}^2 + a_{wy}^2 + a_{wz}^2]^{\frac{1}{2}} . \quad (13)$$

Table 3. ISO 2631-1 Frequency Weightings and Multiplying Factors

Direction	HEALTH RISK Seat Pan		COMFORT REACTION			
	Frequency Weighting	Multiplying Factor	Seat Pan Frequency Weighting	Multiplying Factor	Seat Back Frequency Weighting	Multiplying 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	$k = 0.4$

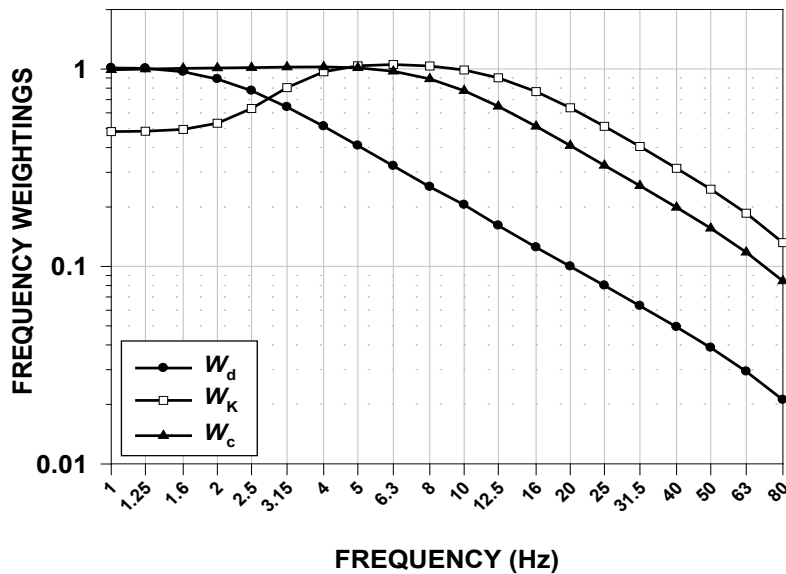


Figure 5. ISO 2631-1 Frequency Weightings W_d , W_k , and W_c

If the vibration at the seat back is also measured, the overall vibration total value (oVTV) is calculated as the vector sum of the seat pan and seat back pVTVs. The seat pan pVTV or oVTV are 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 is used after applying the appropriate multiplying factors given in Table 3 for health risk. The ISO 2631-1: 1997 also states that the vector sum, a_p , of the weighted accelerations at the seat pan, using Equation 13, can be used when vibration in two or more axes are similar after applying the

appropriate multiplying factors for health risk (Table 3). Figure 6 illustrates the ISO 2631-1 Health Guidance Caution Zone associated with the ISO basic evaluation method. For daily overall weighted accelerations falling below the lower boundary of the ISO Health Guidance Caution Zone for the expected daily exposure 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 comfort and health risk assessments are typically applied to field data to gauge aircrew exposures that may lead to recommendations for vibration mitigation.

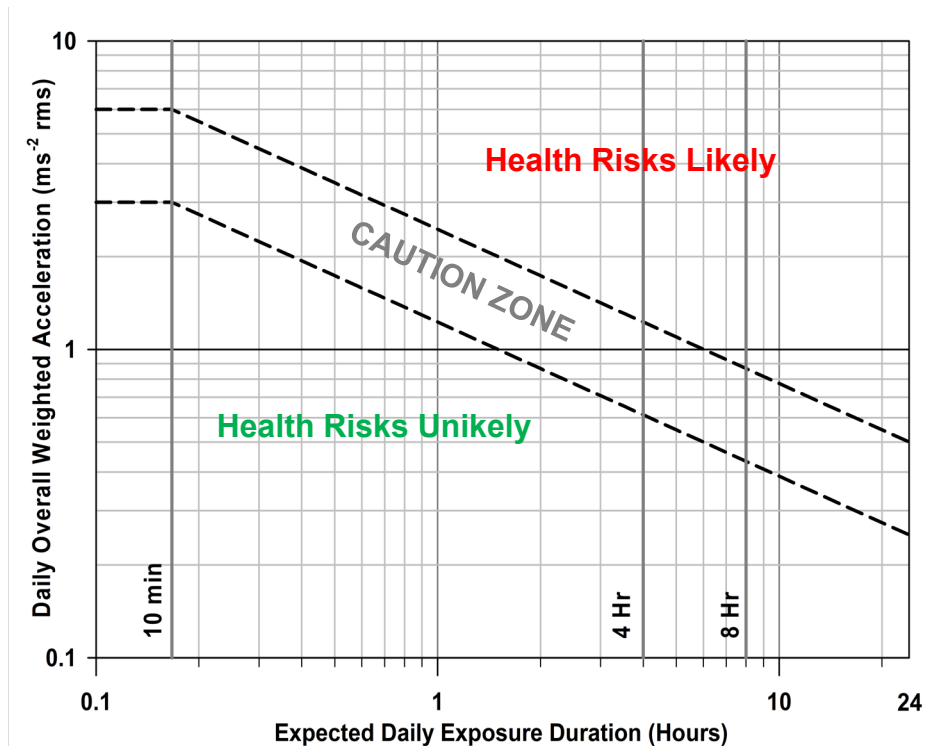


Figure 6. Health Guidance Caution Zone (ISO 2631-1, Annex B)

4.4 Percent (%) Vibration Reduction

The funding agency or customer will most likely require the seat vendor to reduce the vibration by a certain percentage. They may not be specific as to the site, direction, or specific metric targeted for this reduction. The BPF peaks (and/or other prominent peaks), overall unweighted accelerations, and overall weighted accelerations can be used to gauge this reduction at specific sites. At a minimum, this should include the seat pan interface. The percent reduction in vibration can be calculated as:

$$\text{Percent (\%) Reduction} = [(a_{\text{original seat}} - a_{\text{prototype seat}}) / a_{\text{original seat}}] * 100 \quad (14)$$

where

- a = $a_{l,Peak}, a_l, a_{wl}, pVTV, oVTV, a_v$,
- $a_{l,Peak}$ = BPF peak acceleration in direction, l (or other pertinent peak), m/s^2 rms,
- a_l = Overall unweighted acceleration in direction, l , m/s^2 rms (Equation 11),
- a_{wl} = Overall weighted acceleration in direction, l , m/s^2 rms (Equation 12),
- $pVTV$ = Point Vibration Total Value at the seat pan/seat back for comfort assessment (Section 4.3.2),
- $oVTV$ = Overall Vibration Total Value for comfort assessment (Section 4.3.2),
- a_v = Vector sum of the overall weighted accelerations for health risk (Section 4.3.2).

5.0 DATA ANALYSIS

As mentioned in the INTRODUCTION, data from the study conducted by AFRL 711 HPW in 2018 (Smith, S.D., et al., 2019) are being used to illustrate the analyses and presentation of data and results that have been explored in the development of the PoC methodology. The referenced report for this study has been cleared for public release. This particular study sought to evaluate the vibration mitigation characteristics of a seat suspension technology installed on a SH-60S seat. The seat is identical to the original seats installed on other variants of the Blackhawk. The suspension system was designed with a damper filled with a magnetorheological fluid. The seat configurations included LOCKED (representing the original seat with no damper), UNLOCKED OFF (constant viscosity damper), and UNLOCKED ON (active variable viscosity damper). Data from the LOCKED and UNLOCKED OFF damper configurations are used in this document for illustrative purposes. The UNLOCKED OFF damper configuration is presented as UNLOCKED. The 2018 study included additional types of exposures and the measurement and analysis of physiological responses, which are beyond the scope of the PoC methodology. In addition to the FLAT SPECTRUM signal, exposures included multi-axis vibration at 17 Hz (BPF) and two signals representing vibration measured on the HH-60M (Smith, S.D., et al., 2014). The HH-60M includes an Automatic Vibration Suppression System (AVSS) or Active Vibration Control System (AVCS) which targets vibration mitigation in the vertical (Z) direction. One signal included in the 2018 study represented level flight with the AVSS ON. The second signal represented level flight with the AVSS OFF. The data associated with the AVSS ON are being used as the examples presented below.

5.1 R.M.S. Acceleration Spectra

It is recommended that the results first provide summary information regarding the R.M.S. acceleration spectra described in Section 4.1. At a minimum, this should be done using the triaxial accelerations measured at the seat pan interface for the various seat configurations. As mentioned in Section 4.1, the main objective is to confirm the similarity in the frequency location of the peak responses and to identify any obvious differences in the peak amplitudes and frequency distribution between the seat configurations. Note that, any comparative observations regarding the peak responses can only be made if the input vibration at the floor is similar among the seat configurations. It is important to compare the floor measurements among the seat configurations to ensure this is the case. Depending on the vibration platform characteristics, and particularly if the field signal includes substantial vibration at higher frequencies well beyond 80 Hz, there could be coupling between the platform and the particular seat configuration. This coupling may cause variable vibration input at the floor that will subsequently influence the output measurements. In this situation, the analysis will need to account for these differences, i.e., by considering a data normalization process.

Figure 7 compares the FLAT SPECTRUM seat pan spectra for one subject from the study conducted in 2018. Both seat configurations showed notably higher vibration beyond 40 Hz in the fore-and-aft (X) direction among all subjects. As mentioned in Smith, S.D., et al., 2019, the specific differences between the two seat configurations at these higher frequencies were most likely influenced by the seat adjustment mechanism and/or the addition of the suspension components to the back of the seat. For this particular subject, Figure 7 does show a downward

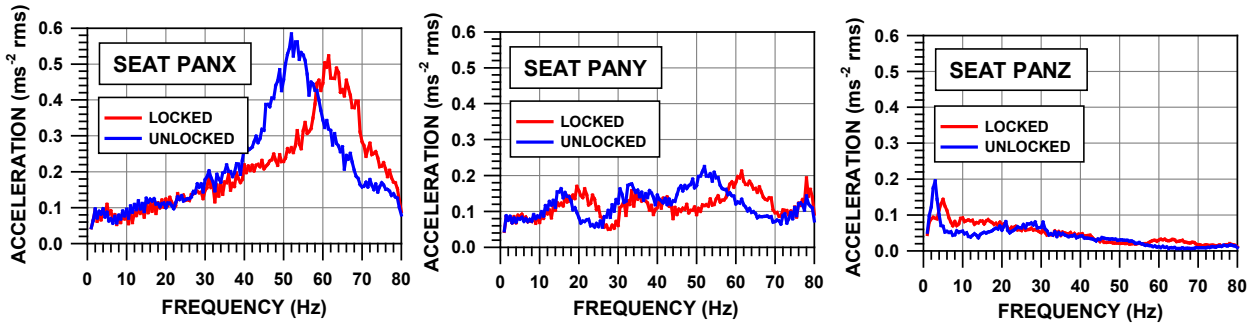


Figure 7. Sample R.M.S. Acceleration Spectra – FLAT SPECTRUM Exposure

shift in the low frequency vertical (Z) peak associated with human whole-body resonance (4-5 Hz) to 2-3 Hz, with some damping at frequencies below 20 Hz with the UNLOCKED configuration. The trends observed in Figure 7 were basically observed among the other subjects, although many showed more vertical damping beyond 20 Hz. The downward shift in the peak frequency in the vertical (Z) direction is associated with typical vehicle suspension behavior and was observed for all subjects. With the FLAT SPECTRUM, all frequency components at the floor were at about the same amplitude level among all subjects and for both seat configurations. Therefore, the shape of the distribution of the acceleration amplitudes over the frequency range should closely represent the shape of the frequency distribution of the transfer function at the targeted measurement sites. This may render the presentation and discussion of the FLAT SPECTRUM responses unnecessary if the transfer function is included in the analysis.

Figure 8 compares the HH-60M AVSS ON seat pan spectra for one subject from the 2018 study. The figure clearly shows the prominent acceleration peak occurring at the BPF (17 Hz) with the AVSS ON for both seat configurations. For the subject data depicted in the figure, there appeared to be an amplification of the fore-and-aft (X) BPF peak and some damping of the lateral (Y) and vertical (Z) BPF peaks with the UNLOCKED configuration. Figure 8 does show that the highest BPF peak at the seat pan occurred in the lateral (Y) direction. This was also observed in the field data at the pilot seat base (underside of seat; vibration could not be measured on the floor beneath the pilot seat). The distinct BPF peak consistently observed in all three directions in Figure 8 may be a good target for comparing between seat configurations,

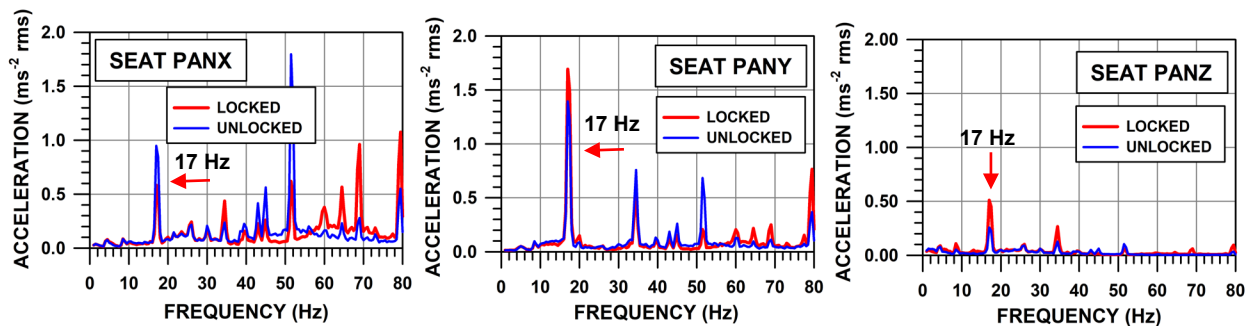


Figure 8. Sample R.M.S. Acceleration Spectra – HH-60M AVSS ON Exposure

particularly if the intent of the prototype design is to mitigate this persistent and prominent peak (Section 5.3).

5.2 Transfer Functions

As mentioned in Sections 4.1.1 and 4.1.2, there are nine (9) transfer functions and (9) coherences that can be calculated that include off-axis effects. It is important to look at all nine (9) transfer functions to gauge potential off-axis influences that could be important with regard to vibration mitigation. Figure 9 illustrates the mean transmissibilities (top) and mean partial coherences (bottom) calculated with seven (7) subjects, including the subject shown in Figure 7, where the output measurement at the seat pan is in the same direction as the input measurement at the floor (Smith, S.D., et al., 2019). There appeared to be minimal effect of off-axis vibration in this particular study, which simplifies the analysis of vibration transmission. In the example

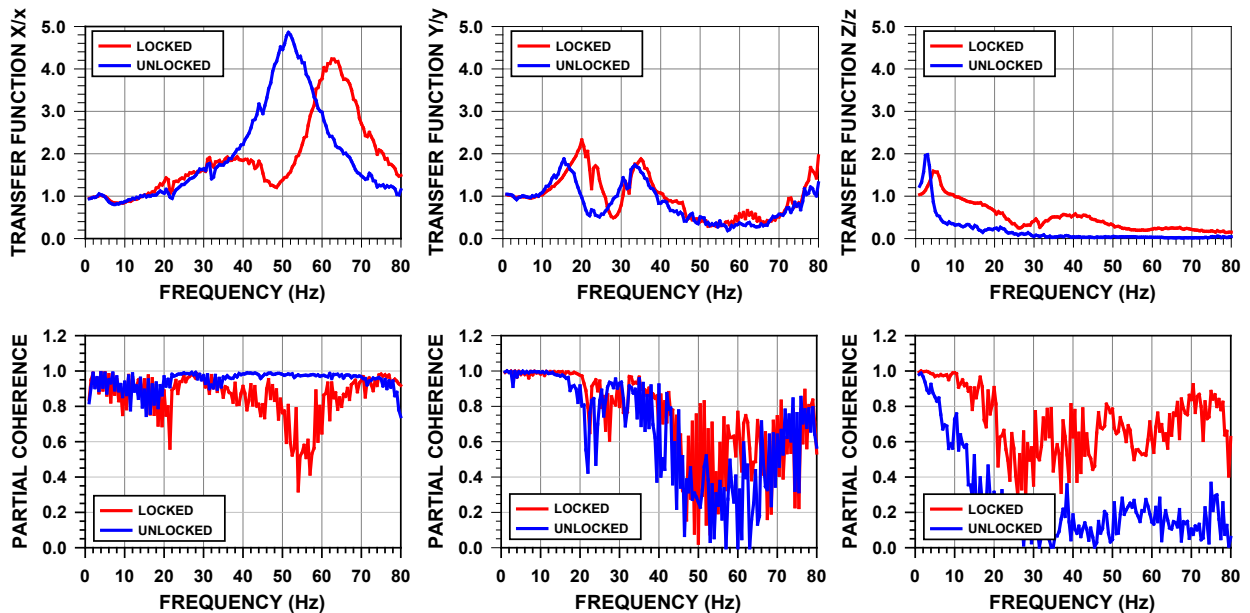


Figure 9. Sample Seat Pan Transfer Functions (Transmissibility)

given, the mean response among the subjects was found to be a good representation of the response observed for each subject. It is noted that the shape of the plots in Figure 9 are similar to the shape of the plots shown in Figure 7. The higher fore-and-aft (X) BPF peak and lower lateral (Y) BPF peak illustrated in the R.M.S. acceleration spectra for one subject with the UNLOCKED seat (Figure 8) are not clearly predicted by the transfer functions. In addition, both seat configurations show similar transmission of vibration that is also similar to the input vibration at the floor between about 0 – 20 Hz in the fore-and-aft (X) direction and between about 0 and 10 Hz in the lateral (Y) direction (Transfer Function ~ 1.0). The UNLOCKED seat did mitigate the transmission of lateral (Y) vibration at frequencies just beyond the BPF. The UNLOCKED seat configuration also shifted the vertical (Z) peak associated with whole-body resonance to a lower frequency. While both seat configurations appeared to damp the vertical (Z) input vibration at the floor beyond the low frequency peak, the UNLOCKED seat further

mitigated the transmission of vertical (Z) vibration at frequencies below 20 Hz, including at the BPF, as compared to the LOCKED seat. In addition, the UNLOCKED seat also mitigated higher frequency vibration in the vertical (Z) direction, which may include multiples of the BPF. This was not observed in Figure 7 for one subject, but was observed for other subjects. It is noted that the field data associated with the Blackhawk studies listed in Table 1 did not show any prominent vibration generated at the floor or seat base in the vicinity of the PRF. This may not be the case in other aircraft, or if the propeller blades are not appropriately balanced. If the PRF peak is shown to be a major contributor to the overall weighted vibration used to assess comfort and health risk, this should be addressed in the PoC study, since human response is quite sensitive to these low frequencies.

The partial coherences show relatively high values (0.8 or greater) at the lower frequencies. This has been observed with other seat tests conducted by AFRL 711 HPW. The lower coherences indicated that the output response had a relatively low linear relationship with the input, or that other factors or noise may have contributed to the output at the higher frequencies. In addition, low partial coherence appeared to be associated with low output responses. Although not shown, the multiple coherence can be even more difficult to interpret since the value reflects how well the three known inputs contribute to the targeted output. The values tended to be close to 1.0 across the frequency range in the Smith, S.D., et al., 2019 study.

A comparison between the results using the multiple input model vs the single input model with one of the subjects from Smith, S.D., et al. 2019 showed minor differences between the transmissibilities or amplitudes of the transfer function. The ordinary coherences tended to be lower as compared to the partial coherences. Either one of the models is considered suitable for comparing the transmission characteristics between the seat configurations. Both provide valuable information regarding seat performance over the frequency range of interest for human exposure.

5.3 Peak Accelerations

The distinct BPF peak consistently observed in all three directions in Figure 8 may be a good target for comparing between seat configurations, particularly if the intent of the prototype design is to mitigate this prominent peak occurring below 20 Hz. Figure 10 compares the mean BPF peak \pm one standard deviation, extracted from the HH-60M AVSS ON spectra, for the two seat configurations. Table 4 lists the seat pan and seat back BPF peaks among the seven (7) subjects and includes the mean \pm one standard deviation for the two seat configurations. A simple paired t-test was done with significance at $P < 0.05$. Significant results are marked with an asterisk. The figure confirms the similarity in the floor input peaks between the two seat configurations. As suggested in Figure 8, the UNLOCKED seat (prototype) produced significantly higher fore-and-aft (X) seat pan BPF peaks, but significantly mitigated the lateral (Y) and vertical (Z) seat pan BPF peaks, as compared to the LOCKED seat (original). These findings were not clearly predicted in the transfer functions at the BPF (Figure 9). The UNLOCKED seat significantly increased the fore-and-aft (X) and vertical (Z) seat back BPF peaks, but mitigated the lateral (Y) seat back BPF peaks as compared to the LOCKED seat. It is noted that the highest seat pan and seat back peaks occurred in the lateral (Y) direction. The

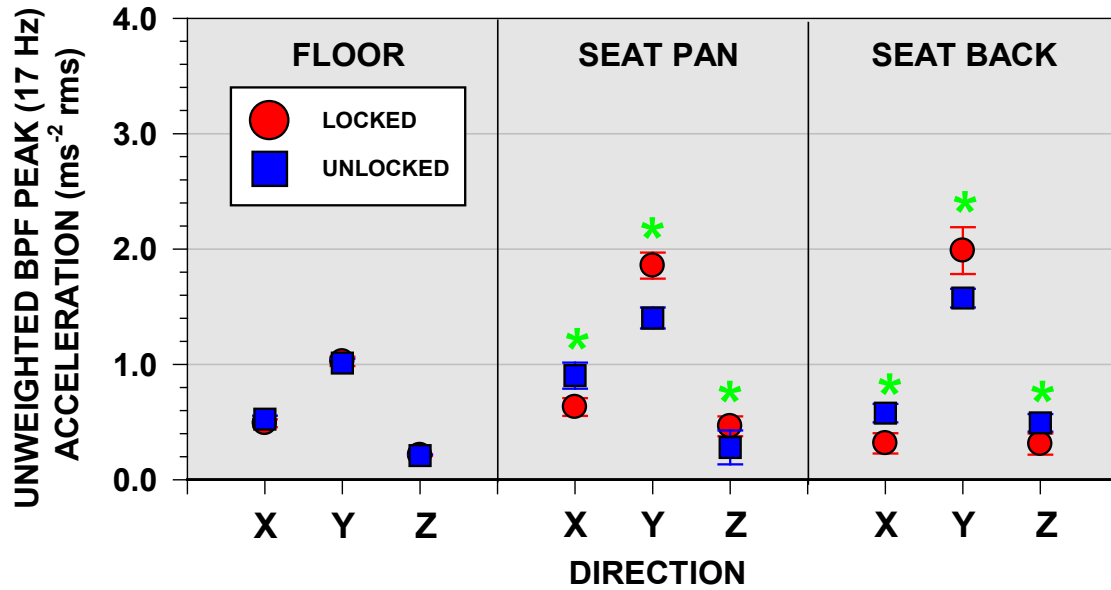


Figure 10. Mean Unweighted BPF Peaks ± One Standard Deviation (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

mitigation of these peaks is notable, since the seat was designed with the intention of mitigating vibration in the vertical (Z) direction, where lower vibration levels were observed.

Table 5 lists the percent (%) BPF peak acceleration reduction occurring with the UNLOCKED seat as compared to the LOCKED seat. The table reflects the observations in Figure 10 and Table 4. Table 5 does show that the percent reduction in the vertical (Z) seat pan BPF peak with the UNLOCKED seat was quite variable among the subjects.

**Table 4. Unweighted BPF Peaks
(HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)**

LOCKED SEAT CONFIGURATION	HH-60M EXPOSURE BPF PEAKS (m-s⁻² rms)					
SUBJECT	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	0.67	2.02	0.50	0.19	2.28	0.42
2	0.52	1.87	0.45	0.40	1.98	0.21
3	0.64	1.89	0.47	0.29	1.94	0.34
4	0.67	1.96	0.53	0.35	2.11	0.31
5	0.58	1.77	0.51	0.44	1.72	0.23
6	0.75	1.79	0.28	0.25	2.12	0.43
7	0.58	1.69	0.51	0.29	1.76	0.22
MEAN	0.63	1.86	0.46	0.31	1.99	0.31
STDEV	0.08	0.11	0.09	0.09	0.20	0.09
UNLOCKED SEAT CONFIGURATION	HH-60M EXPOSURE BPF PEAKS (m-s⁻² rms)					
SUBJECT	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	1.00	1.44	0.07	0.64	1.70	0.53
2	0.69	1.42	0.31	0.46	1.57	0.44
3	0.96	1.49	0.39	0.54	1.57	0.44
4	0.99	1.29	0.35	0.64	1.49	0.51
5	0.82	1.50	0.47	0.55	1.48	0.54
6	0.91	1.27	0.11	0.69	1.56	0.39
7	0.95	1.39	0.26	0.52	1.66	0.61
MEAN	0.90	1.40	0.28	0.58	1.57	0.49
STDEV	0.11	0.09	0.15	0.08	0.08	0.08

**Table 5. Percent (%) Unweighted BPF Peak Acceleration Reduction
(HH-60M AVSS ON, Smith, S.D., et al. 2019)**

SUBJECT	PERCENT (%) BPF PEAK ACCELERATION REDUCTION					
	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	-49.86	28.40	85.95	-243.20	25.39	-26.95
2	-31.98	24.36	30.51	-15.86	20.77	-111.02
3	-49.87	21.36	15.95	-87.05	19.09	-27.27
4	-47.97	34.02	33.76	-82.01	29.44	-65.18
5	-42.32	14.82	7.65	-24.23	13.85	-137.11
6	-21.38	29.05	61.00	-174.94	26.44	9.95
7	-62.59	17.63	49.75	-82.81	5.67	-171.99
MEAN	-43.71	24.24	40.65	-101.44	20.09	-75.65
STDEV	13.47	6.79	27.07	81.36	8.21	66.41

- Greater than 50% vibration reduction with Unlocked Seat
- Greater than 25% but less than 50% vibration reduction with Unlocked Seat
- Greater than 0% but less than 25% vibration reduction with Unlocked Seat
- Vibration amplification with Unlocked Seat

5.4 Overall Unweighted Acceleration (1-80 Hz).

The overall unweighted acceleration at each of the measurement sites can be compared between seat configurations to gauge the relative performance of the seat over the targeted frequency range of interest. Figure 11 illustrates the overall unweighted acceleration \pm one standard deviation at the floor, seat pan, and seat back among the seven (7) subjects. Table 6 lists the seat pan and seat back overall unweighted acceleration levels among the seven (7) subjects and includes the mean \pm one standard deviation for the two seat configurations. The paired t-test was applied to determine significance at $P < 0.05$. Significant differences are annotated with an asterisk. It is important to include the floor values to show the negligible variation of the input vibration not only among the subjects but also between the seat configurations. Note that the overall vertical (Z) levels at the floor did show significant differences between the seat configurations but the plot suggests these differences were relatively small. The overall fore-and-aft (X) seat pan and seat back levels do not show the significant difference seen in Figure 10 with the BPF peaks, but do show relatively large variability among the subjects when considering the unweighted responses at higher frequencies. The higher seat pan overall unweighted horizontal (X, Y) levels (Figure 11) as compared to the seat pan horizontal (X, Y) BPF peaks (Figure 10) does illustrate the substantial contribution of vibration beyond the BPF, including vibration at multiples of the BPF. This contribution is observed in the Figure 8

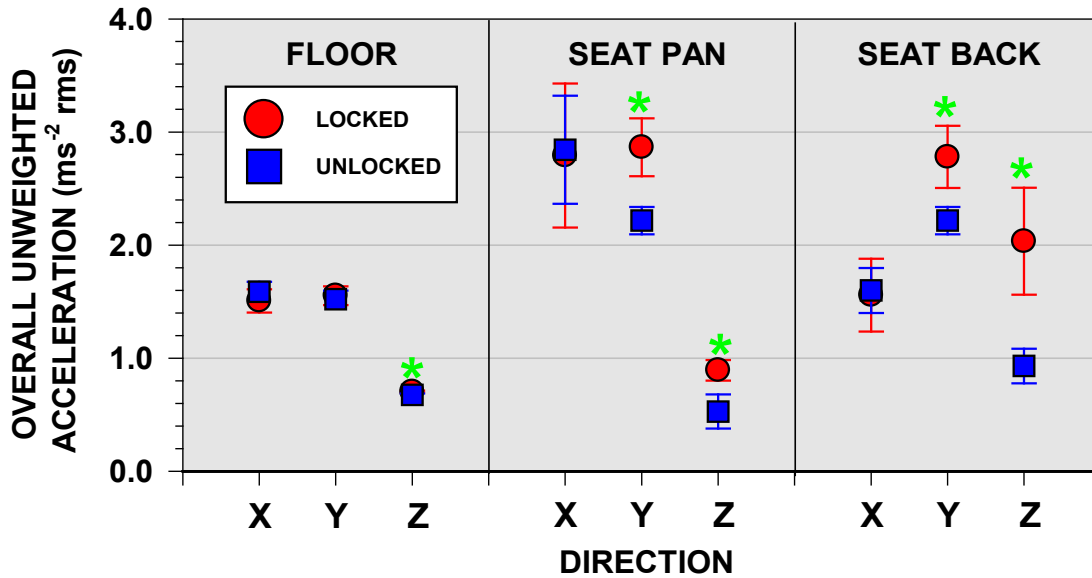


Figure 11. Mean Overall Unweighted Acceleration ± One Standard Deviation (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

example, particularly in the fore-and-aft (X) direction, and, to some extent, in the lateral (Y) direction. The overall vertical (Z) seat back levels were significantly higher with the LOCKED seat, opposite the effect observed in Figure 10. Again, this is most likely due to significant contributions from higher frequency vibration and, specifically, multiples of the BPF at the seat back with the LOCKED seat. The mitigation of these higher frequencies may be important relative to the general aircrew perception of the vibration even though their contribution to the ISO assessment of comfort and health risk are limited due to the frequency weightings (Section 5.4). In summary, the figure and table do show that, for this comparison, the UNLOCKED seat mitigated the lateral (Y) and vertical (Z) seat pan and seat back unweighted vibration levels with minimal effect in the fore-and-aft (X) vibration.

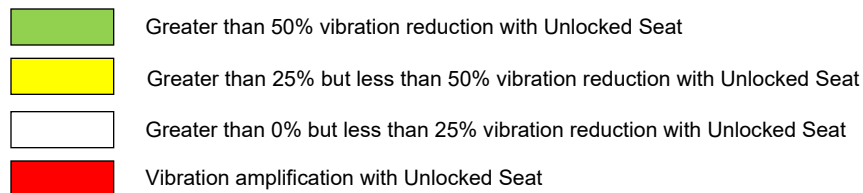
**Table 6. Overall Unweighted Accelerations
(HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)**

LOCKED SEAT CONFIGURATION	HH-60M EXPOSURE OVERALL UNWEIGHTED ACCELERATION (m-s⁻² rms)					
SUBJECT	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	4.21	3.39	0.97	1.90	3.21	2.99
2	2.59	2.81	0.93	1.92	2.75	1.56
3	2.44	2.77	0.86	1.25	2.70	1.92
4	2.43	2.99	1.00	1.79	2.91	1.80
5	2.51	2.71	0.92	1.56	2.43	1.71
6	2.61	2.68	0.73	1.14	2.97	2.20
7	2.74	2.69	0.84	1.34	2.49	2.06
MEAN	2.79	2.86	0.89	1.56	2.78	2.03
STDEV	0.64	0.26	0.09	0.32	0.27	0.47
UNLOCKED SEAT CONFIGURATION	HH-60M EXPOSURE OVERALL UNWEIGHTED ACCELERATION (m-s⁻² rms)					
SUBJECT	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	3.66	2.72	0.33	1.65	2.41	1.08
2	2.24	2.11	0.48	1.39	2.17	0.76
3	2.43	2.29	0.64	1.25	2.2	1
4	2.9	2.23	0.62	1.67	2.09	0.85
5	2.6	2.43	0.74	1.7	2.09	0.93
6	2.92	2.3	0.36	1.76	2.21	0.75
7	3.15	2.41	0.52	1.76	2.35	1.14
MEAN	2.84	2.36	0.53	1.60	2.22	0.93
STDEV	0.48	0.19	0.15	0.20	0.12	0.15

Table 7 lists the percent (%) overall unweighted acceleration reduction occurring with the UNLOCKED seat as compared to the LOCKED seat. The table shows that any overall unweighted fore-and-aft (X) seat pan and seat back vibration reduction was less than 25% (with a few exceptions), with several subjects showing a vibration increase with the UNLOCKED seat. Lateral (Y) seat pan and seat back overall unweighted vibration reductions with the UNLOCKED seat were mostly below 25%. Vertical (Z) seat pan and seat back overall unweighted vibration reductions with the UNLOCKED seat were greater than 25% (for all but one subject at the seat pan). These results are reflective of the trends observed in Figure 11.

Table 7. Percent (%) Overall Unweighted Acceleration Reduction (HH-60M AVSS ON, Smith, S.D., et al. 2019)

SUBJECT	PERCENT (%) OVERALL UNWEIGHTED ACCELERATION REDUCTION					
	SEAT PAN			SEAT BACK		
	X	Y	Z	X	Y	Z
1	13.05	19.67	66.12	13.31	24.94	74.58
2	13.51	24.91	48.39	27.60	21.09	35.90
3	0.41	17.33	25.58	0.00	18.52	55.73
4	-19.34	25.42	38.00	6.70	28.18	48.33
5	-3.59	10.33	19.57	-8.97	13.99	56.14
6	-11.88	14.18	50.68	-54.39	25.59	48.18
7	-14.96	10.41	38.10	-31.34	5.62	63.11
MEAN	-3.26	17.46	40.92	-6.73	19.71	54.57
STDEV	13.11	6.26	15.78	27.95	7.83	12.29



5.5 Discomfort and Health Risk Assessments (ISO 2631-1)

5.5.1 Comfort Reaction Comparison.

The Comfort Reactions provided in ISO 2631-1 may or may not be valuable in the context of military aircrew vibration exposure, since they are based on the expected response of individuals traveling aboard public transport. However, the comparison of the reactions associated with the tested seat configurations may provide some insight into noteworthy changes regarding discomfort. This may or may not contribute any valuable information to the PoC analysis. Figure 12 illustrates the mean overall accelerations, $pVTVs$, and $oVTVs \pm$ one standard deviation at seat pan and seat back among the seven (7) subjects for the two seat configurations. Included are the ISO Comfort Reactions. The paired t-test was applied to estimate significant differences ($P < 0.05$). Significant differences are annotated with an asterisk. The most noteworthy effect on comfort occurred at the seat pan in the vertical (Z) direction. The estimated discomfort associated with the UNLOCKED seat was considered “a little uncomfortable” among the subjects, as compared to the LOCKED seat that was considered “fairly uncomfortable”, based on the weighted acceleration values. Again, it is not clear how this should be interpreted relative to aircrew exposures but the vibration mitigation did cause a change in the ISO comfort reaction.

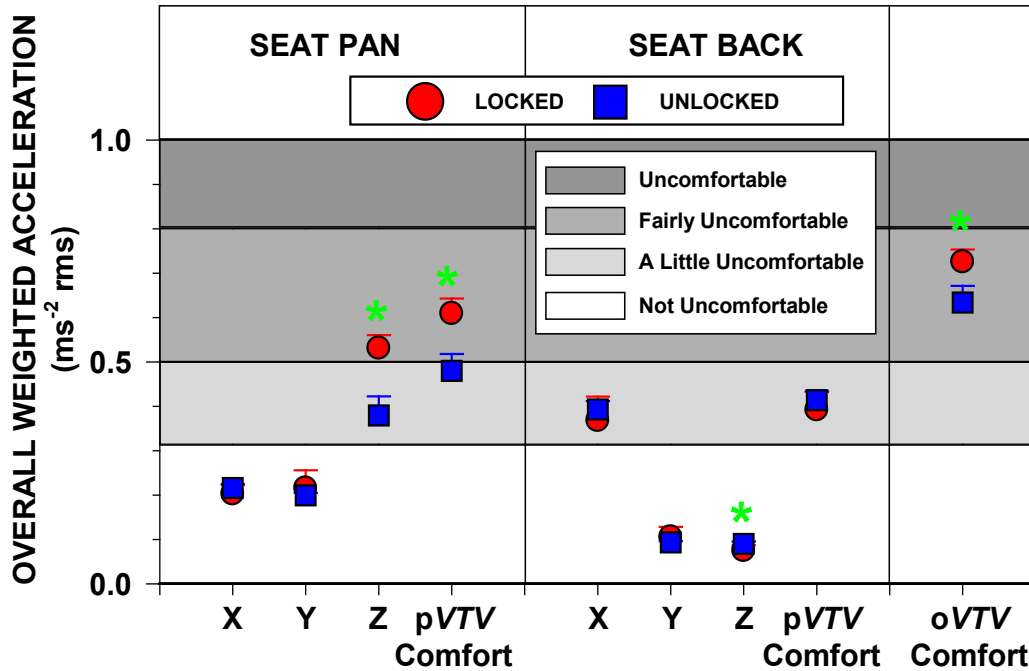


Figure 12. Mean Overall Weighted Accelerations, pVTVs, and oVTVs ± One Standard Deviation for Assessing ISO Comfort Reaction (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

5.5.2 Health Risk Comparison.

This PoC methodology recommends the inclusion of the vector sum of the overall weighted accelerations in the three orthogonal directions, a_v , in accordance with Equation 13, for the health risk analysis. Note that the assessment of health risk is restricted to the seat pan weighted accelerations, and that a_{wx} , a_{wy} , and a_{wz} are calculated using the multiplying factors, k_l , defined in Table 3 for health risk.

Figure 13 illustrates the mean seat pan overall weighted accelerations and vector sum, a_v , ± one standard deviation among the subjects for the two seat configurations. Included are colored bands that represent ranges of exposure duration thresholds for potential health risk relative to the weighted acceleration (based on the HGCZs shown in Figure 6). Table 8 lists the seat pan overall weighted acceleration levels and a_v among the seven (7) subjects and includes the mean ± one standard deviation for the two seat configurations. The paired t-test was applied to determine significant effects ($P < 0.05$). Significant differences are annotated with an asterisk. It is noted that the highest overall weighted seat pan accelerations occurred in the vertical (Z) direction, in contrast to the observations of the overall unweighted seat pan accelerations (Figure 11). The significant effect on health risk occurred in the vertical (Z) direction, which was also reflected in the vector sum, a_v . It appeared that the contribution of the horizontal (X, Y) vibration did influence the vector sum and the associated duration thresholds. With the LOCKED seat, the overall vertical (Z) levels fell within the 4 – 8 hours duration threshold band, while the vector sum fell within the 2 – 4 hours duration threshold band (Figure 13). With the UNLOCKED seat, the overall vertical (Z) levels fell within the > 8 hours duration threshold band, while the vector sum fell within the 4 – 8 hours duration threshold band.

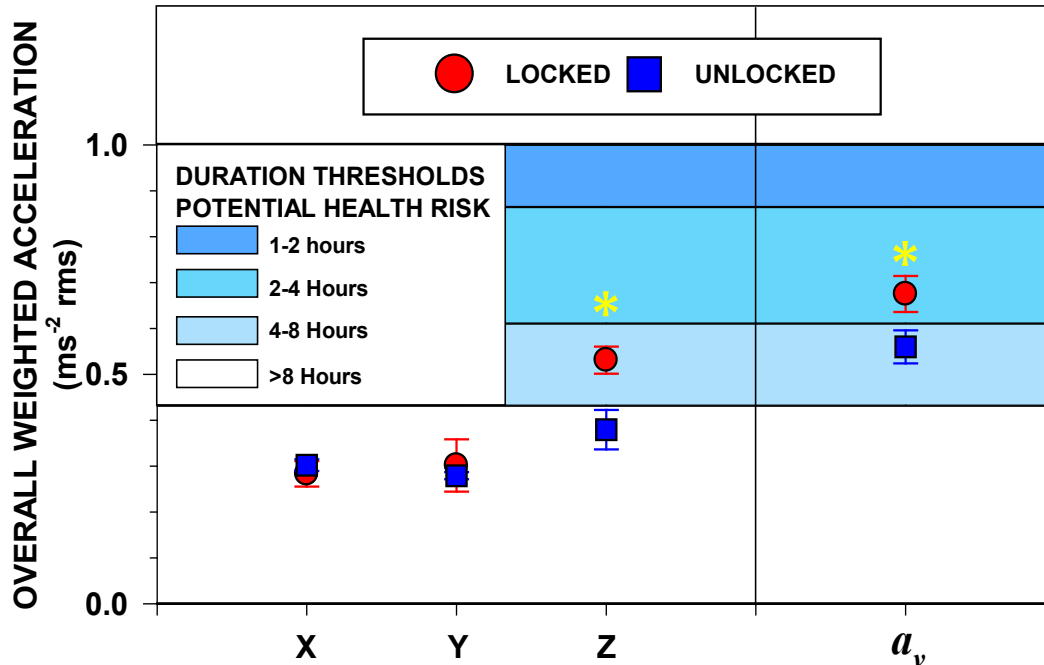


Figure 13. Mean Overall Weighted Accelerations and Vector Sum for Assessing ISO Health Risk (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

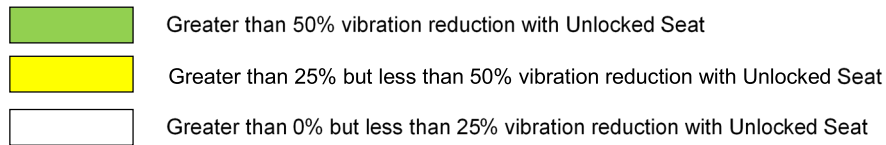
Table 8. Overall Weighted Accelerations and Vector Sum (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

	HH-60M EXPOSURE OVERALL WEIGHTED ACCELERATION and VECTOR SUM (m-s ⁻² rms)							
	LOCKED SEAT				UNLOCKED SEAT			
SUBJECT	SEAT PAN				SEAT PAN			
	X	Y	Z	a_v	X	Y	Z	a_v
1	0.32	0.29	0.54	0.69	0.32	0.28	0.36	0.56
2	0.29	0.28	0.50	0.64	0.28	0.26	0.29	0.49
3	0.23	0.43	0.56	0.74	0.29	0.28	0.39	0.56
4	0.29	0.28	0.58	0.70	0.30	0.29	0.43	0.60
5	0.28	0.27	0.51	0.64	0.30	0.28	0.37	0.55
6	0.29	0.28	0.51	0.65	0.31	0.28	0.40	0.58
7	0.29	0.27	0.52	0.65	0.31	0.28	0.41	0.58
MEAN	0.28	0.30	0.53	0.67	0.30	0.28	0.38	0.56
STDEV	0.03	0.06	0.03	0.04	0.01	0.01	0.04	0.04

Table 9 lists the percent (%) overall weighted seat pan accelerations and a_v reductions occurring with the UNLOCKED as compared to the LOCKED seat. With the contribution of horizontal (X, Y) vibration to a_v , the table shows a lower percent reduction in a_v as compared to the overall weighted vertical (Z) accelerations. The percent reductions in the overall weighted accelerations are also notably lower than the reductions observed in the overall unweighted accelerations, due to the lower contribution of higher frequency components to the overall weighted values that are being effectively reduced with the UNLOCKED seat.

**Table 9. Percent (%) Overall Weighted Acceleration and Vector Sum Reduction
(HH-60M AVSS ON, Smith, S.D., et al. 2019)**

SUBJECT	PERCENT (%) OVERALL WEIGHTED ACCELERATION/VECTOR SUM REDUCTION			
	SEAT PAN			
	X	Y	Z	a_v
1	0.09	1.96	32.67	18.73
2	1.91	4.95	41.25	24.25
3	-27.63	35.26	30.09	24.42
4	-5.89	-0.35	25.91	15.19
5	-6.67	-1.56	26.99	14.09
6	-6.77	-1.61	22.06	10.99
7	-7.01	-1.65	21.23	10.75
MEAN	-7.42	5.29	28.60	16.92
STDEV	9.62	13.44	6.90	5.74



With respect to applying the ISO health risk to military aircrew, it is difficult to determine a daily expected exposure duration, since this can change from day-to-day, week-to-week, etc., depending on the mission. It has been assumed that the field measurements provide a good representation of the average acceleration exposure amplitudes during most missions. These acceleration levels can then be used to calculate the specific exposure duration threshold relative to potential health risk and likely health risk, as defined in Section 4.3.2 and the curve illustrated in Figure 6. The overall weighted seat pan accelerations in the three orthogonal axes or the a_v in the PoC study can be used to calculate the associated exposure duration thresholds for each seat configuration. The comparison of these duration thresholds can be used to gauge the effect of any vibration reduction on the daily aircrew exposure duration limits for safe operation.

The equation for calculating the duration threshold for potential health risk is:

$$T = \frac{(1.5)}{a_v^2}. \quad (13)$$

The equation for calculating the duration threshold for likely health risk is:

$$T = \frac{(6.0)}{a_v^2}. \quad (14)$$

These equations are based on the ISO 2631-1 Annex B and the assumption of equal energy where, relative to a_v

$$a_{v1} \times T_1^{\frac{1}{2}} = a_{v2} \times T_2^{\frac{1}{2}}. \quad (15)$$

Figure 14 illustrates the exposure duration thresholds for potential health risk, based on a_v , for each of the seven (7) subjects with the two seat configurations. Table 10 lists the exposure duration thresholds for potential health risk based on a_v and includes the mean \pm one standard deviation for the two seat configurations. The paired t-test was applied to determine significant effects ($P < 0.05$). As expected, significantly higher exposure duration thresholds ($P < 0.05$) occurred with the UNLOCKED seat as compared to the LOCKED seat for all subjects. Table 10 also lists the differences in the duration thresholds for potential health risk between the two seat

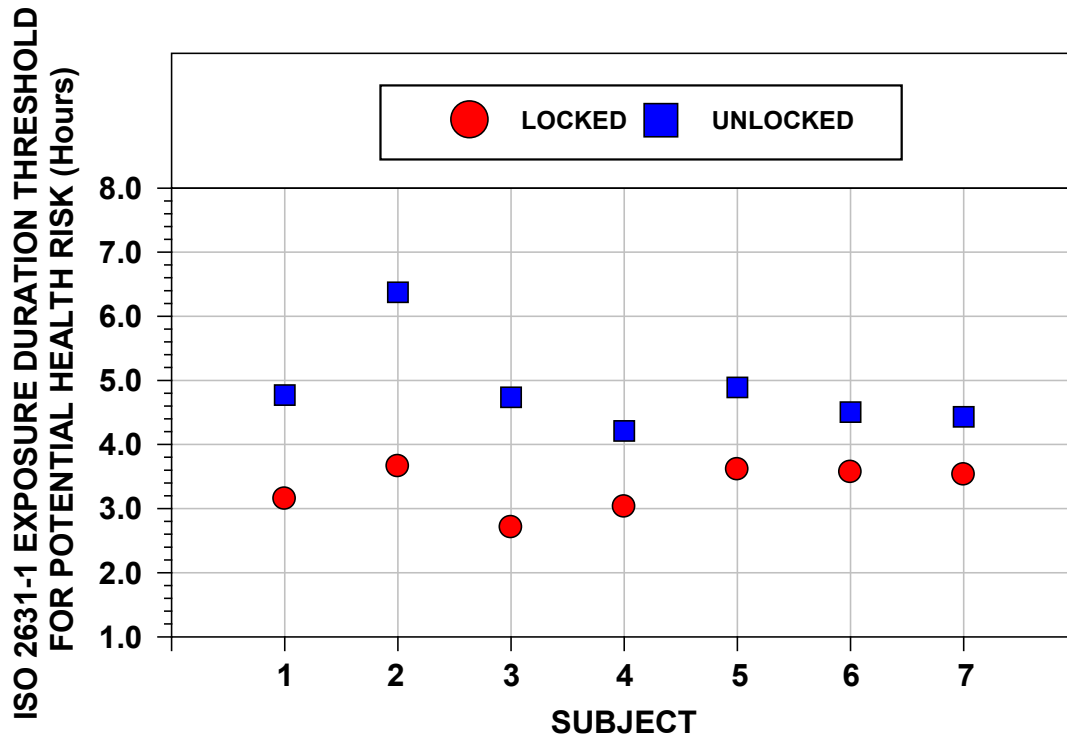


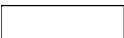



Figure 14. Exposure Duration Thresholds for Potential Health Risk (HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)

configurations for each subject. The differences ranged from 1 to 3 hours with a mean of 1.52 ± 0.66 hours. The percent increases in the duration threshold with the UNLOCKED vs LOCKED seats range from 25.5% to 75% with a mean of $46.7\% \pm 21.0\%$. As with the percent reductions described in Sections 5.4 and 5.5 in the unweighted and weighted overall accelerations, these results are limited to seven (7) subjects but they do illustrate the range of performance improvements with respect to vibration mitigation with the use of the UNLOCKED (prototype)

**Table 10. Exposure Duration Thresholds for Potential Health Risk, Threshold Difference, and Percent (%) Increase
(HH-60M AVSS ON Exposure, Smith, S.D., et al. 2019)**

	HH-60M EXPOSURE DURATION THRESHOLDS, POTENTIAL HEALTH RISK			
	LOCKED SEAT	UNLOCKED SEAT	DIFFERENCE	PERCENT (%) INCREASE
SUBJECT	Hours	Hours	Hours	
1	3.15	4.77	1.62	51.41
2	3.66	6.37	2.72	74.28
3	2.70	4.74	2.03	75.08
4	3.03	4.21	1.18	39.03
5	3.61	4.89	1.28	35.48
6	3.57	4.50	0.94	26.21
7	3.53	4.43	0.90	25.54
MEAN	3.32	4.85	1.52	46.72
STDEV	0.36	0.71	0.66	20.98

-  Greater than 50% vibration reduction with Unlocked Seat
-  Greater than 25% but less than 50% vibration reduction with Unlocked Seat
-  Greater than 0% but less than 25% vibration reduction with Unlocked Seat
-  Vibration amplification with Unlocked Seat

seat.

5.0 DISCUSSION AND CONCLUSIONS

This AFRL Technical Report presents a military aircraft seat vibration mitigation PoC methodology and capability established within the AFRL 711 HPW for human-occupied laboratory test/analysis of vibration mitigation seating system concepts. The methodology was developed based on four studies conducted in the AFRL 711 HPW vibration research facility between 2018 and 2023. Each study contributed new challenges and strategies for evaluating the performance of seat upgrades and redesigns that targeted the mitigation of aircrew vibration aboard rotary-wing and fixed-wing propeller aircraft.

The PoC methodology described in this document requires the comparison of the vibration transmission performance, in a laboratory test facility approved for human use, between the current seating system and a proposed prototype seating system associated with a specific aircraft platform. As mentioned, the prototype seat may include a modification to the existing seat, or may be a completely redesigned seat. The methodology emphasizes that the attachment of each seat configuration should closely resemble that used in the aircraft as much as possible.

It is important to understand the design requirements set forth by the original customer and to have some understanding of the designer's approach to meeting these requirements. As mentioned, these requirements may be very general. The design requirements may just set forth a target percent reduction in vibration, without considering any particular site (i.e., seat pan or seat back interface), direction, or frequency. A goal of the PoC methodology presented in this document was to define several objective metrics, based on the collection of multi-axis acceleration data, that quantify the transmission of multi-axis vibration to the seated human occupant. The methodology requires laboratory exposures that represent the operational environment and recommends exposure to a more generic signal that covers the frequency range of interest. The exposures and metrics were selected for conducting an engineering analysis of occupied seat vibration transmission behavior, as well as for assessing human exposure in accordance with existing human vibration exposure guidelines and standards. These metrics facilitate the comparison between the original seat and prototype seat to characterize vibration mitigation performance.

With regard to the frequency response characteristics, it is essential to calculate the constant bandwidth R.M.S. acceleration spectra at the floor and, at least, at the occupant/seat interface (seat pan) for each subject and each seat configuration, particularly for the exposures representing the aircraft vibration. As mentioned, the main objective here is to confirm the similarity in the frequency location of the peak responses and to identify any obvious differences in the amplitude of peak responses and frequency distribution between seat configurations. An example(s) of the spectra for both seat configurations should be included in any reporting of results. Since rotary-wing and fixed-wing propeller aircraft generate substantial vibration at distinct frequencies, the inclusion of the more generic exposure is recommended for calculating the transfer functions between the input (platform floor) and output (at a minimum, at the seat pan interface). Specifically, a FLAT SPECTRUM signal was used in the studies conducted at AFRL 711 HPW to ensure similar energy across the targeted frequency range. The transfer functions, calculated at the seat pan interface (at the minimum) provide for a detailed mathematical analysis of frequency- and direction-dependent vibration transmission based on

linear theory. As mentioned, this can become quite complex when considering the off-axis linear contributions to the responses and may be beyond the scope of a particular PoC study. As was demonstrated in the specific examples given in Section 5 for the seat pan BPF, the transfer functions may or may not clearly show mitigation characteristics at frequencies associated with the targeted aircraft, depending on the vibration direction. This may be attributed to amplitude-related non-linear effects and/or the influence of cross-axis coupling that may not be easily gauged from these responses.

The evaluation of the substantial peak accelerations that can be extracted from the spectra and the overall unweighted and weighted accelerations provide valuable information relative to the operational exposure(s) with regard to the characterization of seat vibration mitigation performance. Depending on the aircraft, there can be substantial vibration generated at higher frequencies beyond the BPF that may be a concern regarding aircrew perception and ultimately comfort, particularly since military rotary-wing/tilt-rotor and fixed-wing propeller aircraft continuously expose the aircrew to relatively higher frequencies of vibration beyond whole-body resonance. The effects of these higher frequency components are not fully understood. The contribution of these higher frequency components are included in the overall unweighted accelerations. With the overall weighted accelerations, the vibration levels in all three directions are increasingly reduced with increasing frequency by the ISO 2631-1 frequency weightings. As an example, the plots and data provided in Sections 5.4 and 5.5 showed significant vibration damping in the overall unweighted lateral (Y) seat pan accelerations with the UNLOCKED (prototype) seat (Figure 11), as compared to showing no effects in the overall weighted lateral (Y) seat pan accelerations with the UNLOCKED seat (Figure 13). This reflected a significant damping of higher frequency components with the UNLOCKED seat that was not easily seen in the spectra comparison for one subject in Figure 8 (and would be quite difficult to evaluate using the spectra from all subjects). Furthermore, Section 4.3 showed significant damping in the lateral (Y) seat pan BPF peak (17 Hz) with the UNLOCKED seat (Figure 10). It is highly recommended that any PoC testing reports include plots for visualization and tables of actual data for any substantial peaks and both the unweighted and weighted overall accelerations. For these three metrics, it is also recommended to include the percent reduction in vibration with the afforded with the prototype configuration. This will be beneficial to the customer but will also emphasize the relative vibration levels associated with this reduction, and what reductions will be the most beneficial to the aircrew.

Finally, the PoC methodology recommends the calculation of the ISO 2631-1 potential health risk and likely health risk duration thresholds associated with the vector sum of the multi-axis seat accelerations measured during exposure to the operational signal(s). A comparison of these thresholds will be most valuable for considering the effects of any vibration mitigation on daily operation limits and aircrew health risk. The two most important calculations include the duration threshold difference in hours, and the percent increase in threshold provided by the prototype seat. An increase in the threshold is associated with a decrease in the overall weighted acceleration or vector sum. Table 10 shows that, among the seven (7) subjects, there was between a 1 to 3 hour increase with all subjects showing a greater than 25% increase in the allowable daily flight time associated with unlikely health risks. It is up to the customer and/or user to decide if this is sufficient.

All of the metrics described in the PoC methodology provide tools for the customer to determine if the vibration mitigation associated with the tested prototype is sufficient. This PoC methodology was developed with cost and schedule in mind. The laboratory tests and recommended data analysis can be used to improve seat design where further mitigation may be warranted, prior to conducting expensive, disruptive, and time-consuming flight tests.

6.0 REFERENCES

- Bongers, P.M., et al., “Back Pain and Exposure to Whole Body Vibration in Helicopter Pilot”, *Ergonomics*, **33**, 8, 1990, pp. 1007-1026.
- Bendat, J.S. and Piersol A.G., **Engineering Applications of Correlation and Spectral Analysis**, New York, J. Wiley, 1993.
- 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-1472H, Sep, 2020.
- 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.
- Hermes, E.D., Webb, T.S., and Wells, T.S., “Aircraft Type and Other Risk Factors for Spinal Disorders: Data from 19,673 Military Cockpit Aircrew”, *Aviation, Space, and Environmental Medicine*, **81**, 9, Sep, 2010.
- 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.
- Knox, J.B., J.B. Deal, and J.A. Knox, “Lumbar Disc Herniation in Military Helicopter Pilots vs. Matched Controls”, *Aerospace Medicine and Human Performance*, **89**, 5, 2018, pp. 442-445.
- Naidu P.S., **Modern Spectrum Analysis of Time Series**. CRC Press, Boca Raton, 1996.
- Newland D.E., **An Introduction to Random Vibrations and Spectral Analysis**, 2nd ed., New York, Longman Inc., 1984.
- Smith S.D., *Aircrew Vibration Exposure Characterization and Health Risk Assessment of the CV-22 Osprey*, AFRL-RH-WP-2023-0070; AD1217135, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2023.
- Smith, Suzanne D., *Super Cobra (AH-1Z) Human Vibration Evaluation*, AFRL-HE-WP-TR-2005-0114, ADB313268, Distribution B, Wright-Patterson AFB, AFRL Human Effectiveness Directorate, 2005.

- Smith, S.D., Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the MH-65D Dolphin*, AFRL-RH-WP-TR-2019-0103, AD1107319, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2019.
- Smith, S.D., Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the CH-47F Chinook*, AFRL-RH-WP-TR-2020-0074, AD1118408, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2020a.
- Smith, S.D., Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the UH-1N Iroquois*, AFRL-RH-WP-TR-2020-0129, AD1127425, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2020b.
- Smith, S.D., Chervak, S.G., Clasing, J.E., *Vibration Exposure Characterization and Health Risk Assessment of the UH-60L Blackhawk*, AFRL-RH-WP-TR-2019-0032, AD1082363, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2019.
- Smith S.D., Jurcsisn, J.G., Bowden, D. R., *CV-22 Human Vibration Evaluation*, AFRL-RH-WP-TR-2008-0095, ADB345174 (cleared for public release), Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2008.
- 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 Aircraft*, AFRL-RH-WP-TR-2014-0053, ADA604406, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2014.
- Smith, S.D., Steinhauer, BC., Glass, WC., Wells, W., *Vibration Mitigation Analysis of a Seahawk Helicopter Seat Suspension Concept*, AFRL-RH-WP-TR-2019-0033, AD1081874, Distribution A, Wright-Patterson AFB OH: AFRL Human Effectiveness Directorate, 2019.
- Welch, P.D. (1967), "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.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711th Human Performance Wing
ACGIH	American Conference of Governmental Industrial Hygienist
AFRL	Air Force Research Laboratory
AVCS	Active Vibration Control System
AVSS	Automatic Vibration Suppression System
BCA	Business Case Analysis
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
DAS	Data Acquisition System
DoD	Department of Defense
FLTS	Flight Test Squadron
HGCZ	Health Guidance Caution Zone
Hz	Hertz (cycles per second)
ICS	Iterative Control System
IRB	Institutional Review Board
ISO	International Organization for Standardization
MIL-STD	Military Standard
NAS	Naval Air Station
NHSR	Not Human Subject Research
PRF	Propeller Rotation Frequency
PoC	Proof-of-Concept
PSD	Power or Auto Spectral Density
RH	Airman Systems Directorate
SIXMODE	Six Degree-of-Freedom Motion Simulator
TLV	Threshold Limit Value
USCG	United States Coast Guard
USMC	United States Marine Corp ²
ft	feet
kgs	kilograms
lbs	pounds
m/s ²	meters per second squared
R.M.S., rms	root-mean-square
%	percent
a_l	Overall unweighted rms acceleration in direction l (X, Y, Z)
a_{li}	Overall unweighted rms acceleration associated with direction l for the i th frequency component
a_v	Vector sum of the daily overall weighted rms accelerations in directions X, Y, Z
a_{wl}	Overall weighted rms acceleration in direction l (X, Y, Z)
$C_{io}(w)$	Ordinary coherence between input i and output O
$H_{io}(w)$	Complex transfer function for input i and output O
$S_{io}(w)$	Cross-spectrum for input i and output O
$S_{ii}(w)$	Auto-spectrum for input i

$S_{oo}(w)$	Auto-spectrum for output O
k_l	Multiplying Factor for the l direction (ISO 2631-1)
$oVTV(s)$	Overall Vibration Total Value(s)
$pVTV(s)$	Point Vibration Total Value(s)
w	Circular frequency (radians/second)
W_{li}	Frequency Weighting associated with direction l for the specific measurement site (seat pan or seat back) for the i th one-third octave center frequency component
X	Fore-and-Aft Axis or Direction
Y	Lateral Axis or Direction
Z	Vertical Axis or Direction