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The 50th UK Conference on Human Responses to Vibration [Proceedings], 2015

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EVALUATION OF PILOT WHOL-BODY VIBRATION EXPOSURE LEVELS ON A CH-147F CHINOOK MILITARY HELICOPTER

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Abstract

Flight testing has been performed on a Royal Canadian Air Force (RCAF) CH-147F Chinook helicopter to measure pilot whole-body vibration exposure levels during representative flight conditions. Vibration data have been analysed in accordance with the ISO2631-1:1997 standard. The results showed that the helicopter cabin vibration was mainly introduced by the aerodynamic loads at N/rev harmonics of the three-bladed tandem rotor speed. The pilot whole-body vibration levels varied significantly depending on flight conditions and aircraft load configurations. The highest vibration levels occurred during manoeuvres and high speed flight. Referencing to the guidelines in ISO 2631-1:1997, the pilot whole-body vibration exposure level in the tested flight profile were rated as "uncomfortable", and the maximum duration of such a mission should be limited to 1.0 or 3.3 hours depending on the lower or upper limit of the Vibration Health Guideline Caution Zone respectively. The results of a subjective analysis, by the pilot, of the comfort levels during the flight did not provide good correlation with the level of discomfort indices measured during the tested flight profile.

1. Introduction

The helicopter is a versatile air-borne platform built to provide the unique capability of vertical taking-off, landing and hovering. However, the ride quality in a helicopter cabin is often unpleasant due to high vibration and noise levels. Helicopter cabin vibration is primarily excited by the aerodynamic and inertial loads at the N/rev harmonic frequencies of the main rotor. The floor vibration is transmitted through the seat frame and cushions consequently exposing the aircrew to a whole-body vibration environment. Short-term exposure to mechanical vibration transmitted to the human body increases fatigue, degrades comfort, interferes with aircrew performance and affects operational safety (Smith, 2002). Long-term exposure of helicopter aircrew to whole-body vibration is known to contribute to occupational health issues including aircrew neck pain and back pain injuries among many other human-interface related issues in helicopter operations (Castelo-Branco and Rodriguez, 1999; Adams, 2004).

The whole-body vibration levels experienced by helicopter aircrew members are influenced by a number of variables including flight conditions, aircrew size and posture, dynamics of the seat frame and cushions, mission durations as well as rotor balancing status etc. The neck strain and back pain issues are more severe for military aircrew due to the integration of equipment onto the flight helmet and long flight hours during combat operations. For example, the Canadian RCAF has reported mission duration routinely exceeding six hours with the aircrew wearing helmets fitted with night vision goggles. Comfort and health concerns have been raised by the helicopter aircrew members due to the exposure to excessively high vibration and noise levels.

An understanding of the whole-body vibration and noise levels experienced by helicopter aircrew members is essential in the planning of flight missions to ensure aircrew safety and mitigation of long term health issues. On occasion, military helicopter missions such as search and rescue involving rappelling of crew members, as well as the delivery of payloads and weapons may require flight with the cabin doors open. In these cases the helicopter cabin noise levels may exceed exposure limits during specific flight conditions and duration.

This paper presents a flight test evaluation performed by the National Research Council of Canada on a Royal Canadian Air Force (RCAF) CH-147F Chinook helicopter. In this mission, aircrew whole-body vibration and helicopter floor vibration levels were measured for a select number of standard and combat flight conditions and manoeuvres to characterize the vibration environment of the vehicle in representative flight conditions and configurations. The results were analysed in accordance with the ISO2631-1:1997 standard to assess the aircrew whole-body vibration exposure levels. In addition, a survey of the subjective evaluation by the air crew of the level of comfort during the flight conditions was conducted during the test.

2. Flight Test Configuration

2.1. Flight conditions

The objective of the flight test was to characterize the aircrew whole-body vibration exposure in the CH-147F chinook helicopter cabin during various helicopter flights and manoeuvres with the cabin doors closed for normal flight configuration and open to represent combat flight configuration. A RCAF CH-147F Chinook helicopter was instrumented for the investigation. The CH-147F, a Canadian military version of the Boeing CH-47F, is a twin-engine, tandem rotor heavy-lift helicopter. Each rotor is equipped with three blades, and the nominal rotating speed is 215 RPM, or 3.75Hz. The primary roles of this vehicle include troop movement, artillery placement and battlefield resupply.

The aircrew whole-body vibration measurement was performed in accordance with ISO2631-1:1997 entitled "Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-body Vibration - Part 1: General Requirements". Measured aircrew member positions included a portside pilot seat, a starboard side flight engineer seat at STA120 and an occupant seat located at STA320 portside, as schematically shown in Figure 1.

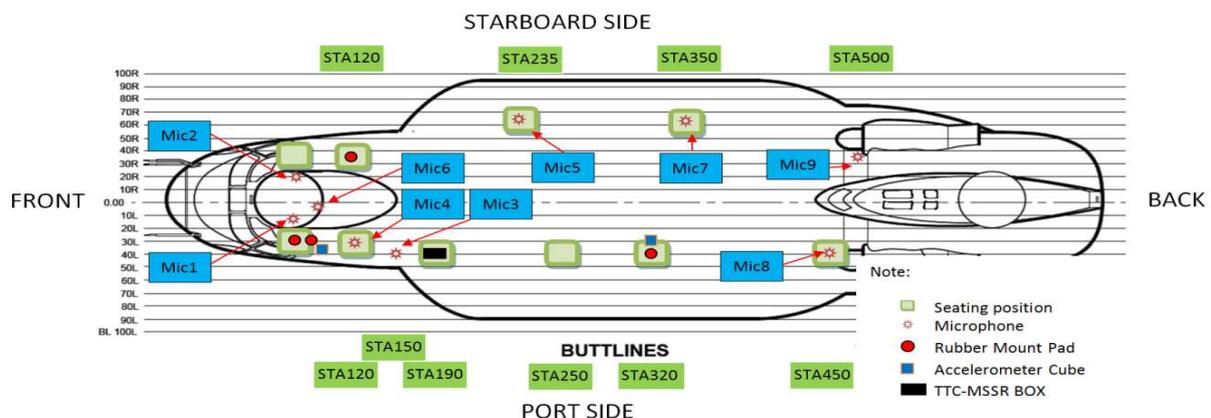


Figure 1: Sensor and aircrew locations in the CH-147F helicopter cabin

The flight test sequence covered three groups, as listed in Table 1. The ground interface manoeuvres included ground running, taking-off, and landing on a paved tarmac. Stationary flight involved hovering in helicopter ground effects at two altitudes of 10 feet and 40 feet, respectively, as well as with a sling load configuration of 4000 lbs(f) at two altitudes of 40 feet and 80 feet, respectively. Steady airspeed manoeuvres included climbing, level, and descending flight. These flight conditions were performed in both doors open and closed configurations.

Table 1: Flight sequence in measurement runs

a) doors open				b) doors closed				
Run ID	Flight Condition	Description	Duration	Run ID	Flight Condition	Description	Duration	
1	Ground	EPUSHA ON	60s	15	Hover	Hoover 10ft door closed	60s	
2		Ground Power, Avionics ON	60s	16		Hoover 40ft door closed	60s	
4		APU ON, Avionics Running	60s	17	Sling	Sling 40ft door closed, hatch closed	60s	
6		APU ON, Engine Levers Idle	60s	18		Sling 80ft door closed, hatch closed	60s	
8b		APU ON, Engine Levers Flight	60s	19	Level	30 kts	60s	
10		APU OFF, Engine Levers Flight	60s	20		80 kts	60s	
11		Hover 10 feet, doors open, hatch open	60s	21		120 kts	60s	
12		Hover 40 feet, doors open, hatch open	60s	22		140 kts	60s	
13		Sling 40 feet door open, hatch open	60s	23		150 kts (optional)	60s	
14		Sling 80 feet door open, hatch open	60s	24		Manoeuvre	80 kts, 30Deg Bank	60s
35	30 kts	60s	25	80 kts, 45 Deg Bank	60s			
36	80 kts	60s	26	100kts, 30 Deg bank	60s			
37	120 kts	60s	27	100kts, 45 Deg bank	60s			
38	140 kts	60s	28	120 kts, Rate 1 Turn	60s			
39	150 kts	60s	29	140 kts, Rate 1 Turn	60s			
40	Manoeuvre	80 kts, 30Deg Bank	60s	30	70kts, Descend Turn, 60Deg		60s	
41		80 kts, 45 Deg Bank	60s	31	70kts, Descend Turn, 60Deg, reverse		60s	
42		100kts, 30 Deg bank	60s	32	Approach		Normal Approach to Hover	60s
43		100kts, 45 Deg bank	60s	33			Normal Approach to No Hover Ldg	60s
44		120 kts, Rate 1 Turn	60s	34		Roll on landing	60s	
45		140 kts, Rate 1 Turn	60s					
46		70kts, Descend Turn, 60Deg	60s					
47		70kts, Descend Turn, 60Deg, reverse	60s					

The maximum flight speed condition during the flight test was 150 knots. Flight conditions for each flight or manoeuvre were maintained for a minimum of 60 seconds to provide a steady operational environment suitable for stationary data recording. The test aircraft layout and instrumentation suite locations are also shown in Figure 1.

2.2. Accelerometer configuration

A total of 18 ICP type accelerometers were used to acquire the whole-body vibration data of the CH-147F aircrew and floor vibration at five locations. Twelve accelerometers were assigned to measure the whole-body vibration of three CH-147F helicopter flight aircrew members at the seat interface. Per ISO2631-1:1997, the tri-axial accelerometers were packaged within four formed rubber mounts and installed at the seat cushion interfaces to avoid alteration of the pressure distribution on the surface of the resilient seat cushion and the aircrew.

On the CH-147F portside pilot seat frame, a standard thin layer of seat cushion was provided to the seat bottom and backrest pads. Two formed rubber mounts were used for vibration measurement at the seat cushion interfaces: one at the pilot-cushion interface of the bottom cushion and the other at the pilot-cushion interface of the backrest cushion. Both formed mount pads were firmly taped to the seat cushion surfaces to avoid sensor movement due to the pilot operations during the flight operations. This configuration is shown in Figure 2a.

In addition to the portside pilot seat, one formed rubber mount was installed at the bottom cushion interface of the flight engineer seat located at the STA120 starboard side. Compared to the pilot seat, a thinner 1 inch thick seat cushion was equipped on the bottom seat pad for the flight engineer seat,

while the backrest was made of a thin layer of canvas fabric. Details of the seat and rubber mount installation are shown in Figure 2b.



2a) pilot seat



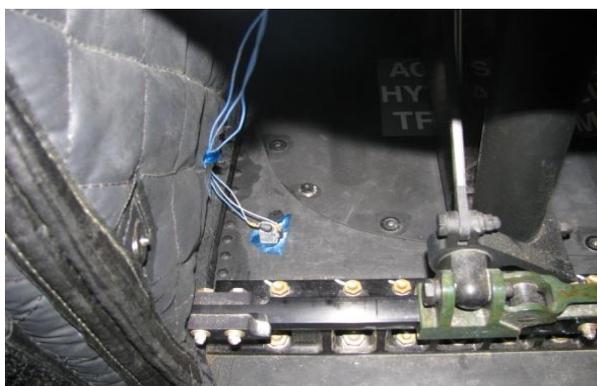
2b) STA120 flight engineer seat

Figure 2: Rubber mounts on the pilot and flight engineer seat cushions



Figure 3: STA320 rubber mount on the passenger cabin seat

One formed rubber mount was installed at the interface of the cabin seat bench located at STA320 portside. Compared to the pilot and flight engineer seats, the seat pad and the backrest of the cabin seat bench were made of canvas fabric only. The rubber mount was also taped to the canvas fabric to avoid movement due to the passenger operations, as shown in Figure 3. In the flight test, the occupant sitting at this location was also chosen to operate the TTC-MSSR vibration data recording device manufactured by the TTC Corp. as shown in Figure 5.



4a) portside pilot seat floor



4b) STA320 portside floor

Figure 4: Accelerometer configurations on the CH-147F helicopter floor

To evaluate the vibration transmission path, helicopter floor vibration levels were also recorded at two floor locations: one underneath the portside pilot seat frame and the other underneath the cabin passenger seat at STA320 portside, as shown in Figure 4. For each location, three ICP type uniaxial accelerometers were attached to a plexiglass® cube using Superglue. The plexiglass® cube was then glued to blue flash tape on the floor to ensure the accelerometers were aligned with the orthogonal X, Y and Z directions of the CH-147F helicopter. This arrangement avoided any damage of, or glue residue on, the helicopter floor.

2.3. Airworthiness considerations



Figure 5: STA190 portable data recording instrumentation box (TTC-MSSR)

A TTC MSSR-100C series miniature data acquisition system was installed on the CH-147F Chinook helicopter as a non-essential item for normal flight operations. This device was configured as a self-powered, standalone unit operating on batteries, and strapped to the passenger bench seat at STA190 portside location, as shown in Figure 5. It is important to note that each functional module of the acquisition system was certified by the manufacturer according to applicable military standards (MIL) and other non-government standards for aircraft flight test purposes. As integrated, the system was not part of the CH-147F helicopter critical flight instrumentation and did not interfere with aircraft operations. This arrangement was approved by the Department of National Defence (DND) authorities to meet the airworthiness requirements for on-board instrumentation in a military aircraft.

3. **Aircrew whole-body vibration exposure**

3.1. Vibration data analysis techniques

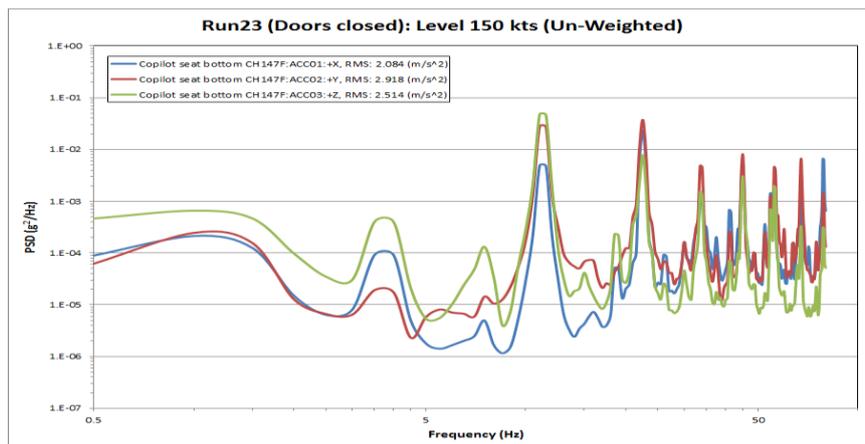
The aircrew whole-body vibration levels on the CH-147F helicopter were measured in each flight condition and analysed independently in accordance with ISO2631-1:1997 through post-analysis. This standard is concerned with the whole-body vibration of a human and is applicable to the assessment of vehicles (air, land and water), machinery and industrial activities that expose people to periodic, random and transient mechanical vibration which can interfere with their comfort, activities and health.

The crest factor (defined in ISO2631-1:1997) of CH-147F vibration data was analysed initially to determine an appropriate analysis method. Since the crest factor in all tested flight conditions was less than 9, the basic evaluation method was deemed sufficient to describe the severity of vibration in relation to its effects on humans. Consequently, the measured vibration data in each flight conditions was evaluated using the basic method defined in Section 6 of ISO2631-1:1997. The recorded

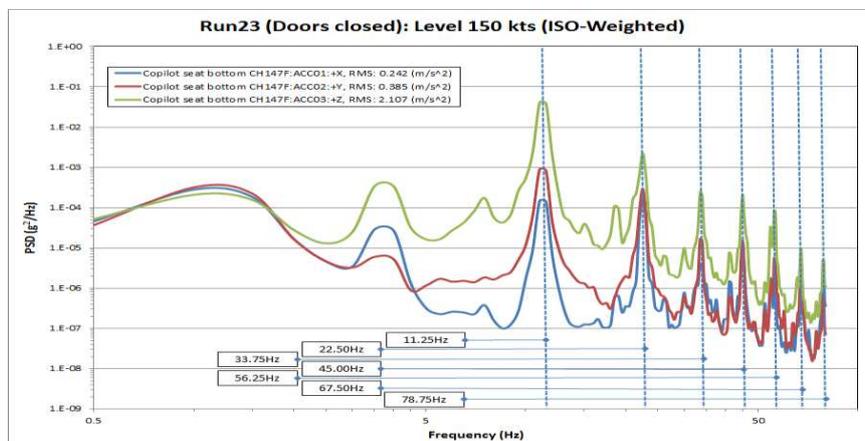
vibration data was used to calculate the weighted root-mean-square (rms) acceleration within the frequency range between 0.5 and 80 Hz by applying appropriate frequency weighting functions and multiplication factors depending on the direction in which the vibration was being measured. The weighted rms vibration levels obtained for each aircrew member were assessed with reference to the “Vibration Health Guidance Caution Zone” in Annex B and “Comfort and Perception Ratings” in Annex C of ISO2631-1997 to determine the severity of whole-body vibration exposure and its potential impacts on aircrew health and comfort.

3.2. Pilot vibration characterization

The whole-body vibration exposure levels of the three aircrew members were evaluated using the basic method defined in ISO2631-1:1997. Aircrew whole-body vibration levels are known to vary depending on many factors including seat location, occupant weight and posture, seat structural dynamics among others. For simplicity of analysis and clarity of reporting data this paper focuses on the whole-body vibration level of the pilot. , For reference, the pilot weighed 190 lb and was 5’9” (1.75 m) in height, which was representative of a 50th percentile male referencing to the statistical anthropometric data of the United States. He was seated at the pilot seat (portside) wearing a HGU-56P-CF flight helmet throughout the flight test.



6a) no weighting

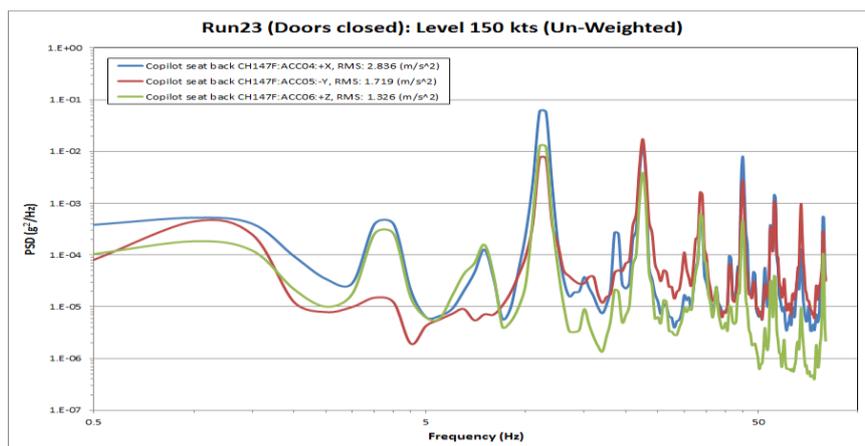


6b) ISO-weighting

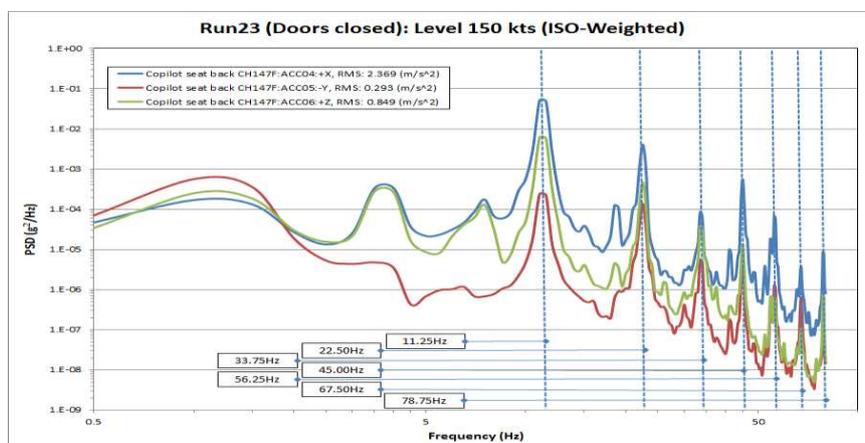
Figure 6: Pilot seat bottom vibration at 150 knots level flight condition

The whole-body vibration level of the 50th percentile pilot during the 150 kts forward flight condition is shown in Figure 6a) and Figure 6b where the blue, red and green lines represent the X, Y and Z directions respectively and the vertical dotted lines indicate the harmonic frequencies of the rotor speed. It was clearly shown that the pilot whole-body vibration was introduced by the N/rev harmonics of the tandem rotor speed. The dominant vibration peaks included the 3/rev at 11.25 Hz and 6/rev at 22.50 Hz, generated by the three-bladed tandem main rotor configuration of the CH-147F helicopter (N=3). Comparing the un-weighted vibration spectra measured in the three orthogonal directions of the pilot bottom seat cushion interface, the vibration levels were found quantitatively close, with 2.1, 2.9 and 2.5 m/s² in the X, Y and Z directions, respectively. After applying ISO weighting, the vibration in the Z direction became dominantly high at 2.1 m/s² while the weighted vibration level was 0.24 and 0.39 m/s² in the X and Y directions respectively.

With reference to the “Comfort and Perception Ratings” presented in ISO2631-1:1997, the pilot whole-body vibration level during the 150 kts forward flight condition was qualitatively rated as “Extremely Uncomfortable”. Consequently, according to the “Vibration Health Guideline Caution Zone”, the suggested maximum exposure time for the pilot was estimated to be between 16.5 and 66 minutes.



7a) no weighting



7b) ISO-weighting

Figure 7: Pilot seat backrest vibration for closed doors configuration at 150 knots level flight

At the pilot seat backrest cushion interface, the dominant vibration peaks also came from the 3/rev and 6/rev harmonics of the tandem main rotor, as shown in Figure 7 where the blue, red and green lines represent the X, Y and Z directions respectively and the vertical dotted lines indicate the harmonic frequencies of the rotor speed. The X direction showed marginally higher vibration level than the Y and Z directions before weighting was applied. However, after applying the appropriate ISO weighting curves, the derived weighted rms vibration level in the X (fore/aft) direction was 2.87 m/s², which was dominantly higher than the 0.29 and 0.85 m/s² weighted levels in the Y and Z directions. Quantitatively, this weighted vibration value in the X direction of the pilot seat backrest was also 33% higher than the weighted vibration level in the Z direction of the pilot seat bottom interface. It is important to note that the X direction of the seat backrest is the normal direction of the backrest cushion interface and the Z direction is the normal direction of the seat bottom cushion interface.

Despite the fact that ISO2631-1:1997 does not provide guidance regarding the seat backrest vibration on human health or comfort, the impact of vibration from the CH-147F pilot seat backrest may require additional investigation because the comparative level of backrest to seat pan vibration may indicate an additional major input that contributes to helicopter aircrew whole-body vibration problems including occupant neck strain and back pain issues. In addition, seat backrest vibration may have a significant effect on pilot performance in conducting his duties during flight.

The vibration transmission from the helicopter floor to pilot seat bottom cushion interface was also analysed and the results are shown in Figure 8. Vibration amplitude reduction was observed for frequency components beyond 12/rev harmonics, or 45 Hz, due to the effective damping provided by the seat bottom cushion materials. However, the vibration amplitudes at the lower harmonic peaks such as 1/rev, 3/rev, 6/rev and 9/rev were not reduced but rather amplified. As a result, the vibration level at the seat bottom cushion interface reached 2.5 m/s² which was higher than the 2.1 m/s² measured on the floor. This amplification effect may have been caused by the coupled dynamics of the seat frame, seat cushion and seat floor as well as the occupant body dynamics during the flight. As a short term solution, improvement to the seat bottom cushion design may be able to provide vibration reduction to the pilot whole-body vibration levels.

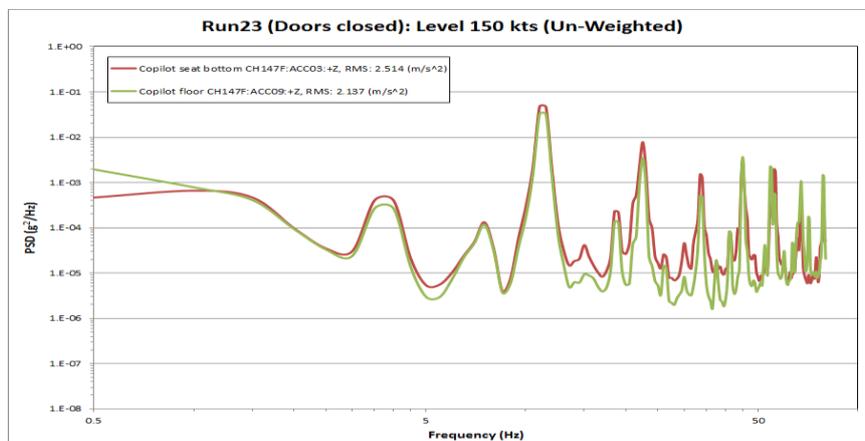


Figure 8: Vibration transmission at the pilot seat location at 150 knots level flight segment

3.3. Whole-body vibration variation with flight conditions

The pilot whole-body vibration levels in the tested flight conditions are shown in Figure 9 where the horizontal dashed blue lines corresponded to the “Extremely Uncomfortable”, “Very Uncomfortable”, “Uncomfortable”, “Little Uncomfortable” and “No Discomfort” levels as suggested in the ISO2631-1:1997. The weighted whole-body vibration level was observed to exceed 1.6 m/s² in 9 flight conditions which were qualitatively rated as “Very Uncomfortable”. These flight conditions included level flights, manoeuvres above 120 kts, sling load flights and approaches to hover. Specifically, in three flight conditions, namely the 150 kts level flight with doors closed, open and the normal approach to hover, the weighted whole-body vibration level exceeded 2.0 m/s² which were qualitatively rated as “Extremely Uncomfortable”. However, results from the doors open and doors closed flight configuration were found to have no appreciable statistical difference in the pilot whole-body vibration levels.

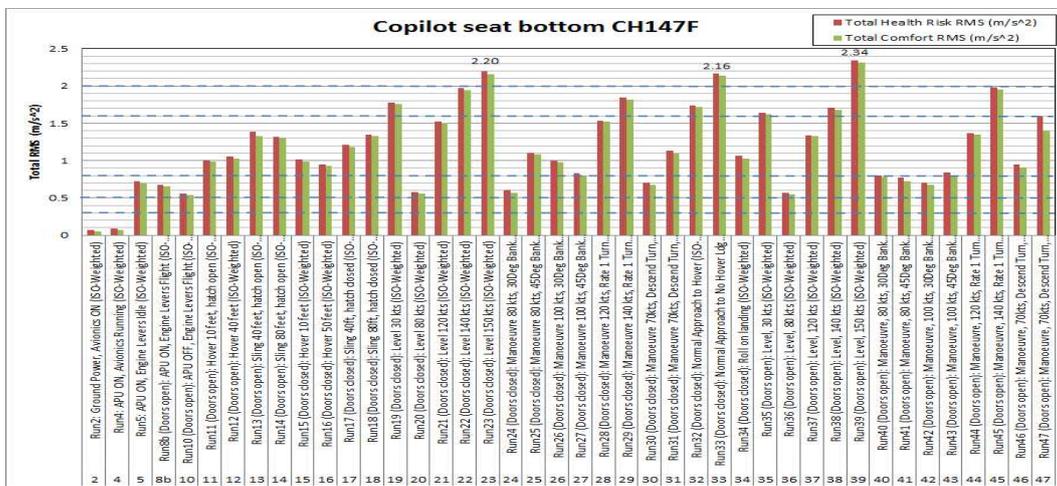


Figure 9: Pilot whole-body vibration levels at seat bottom cushion interface

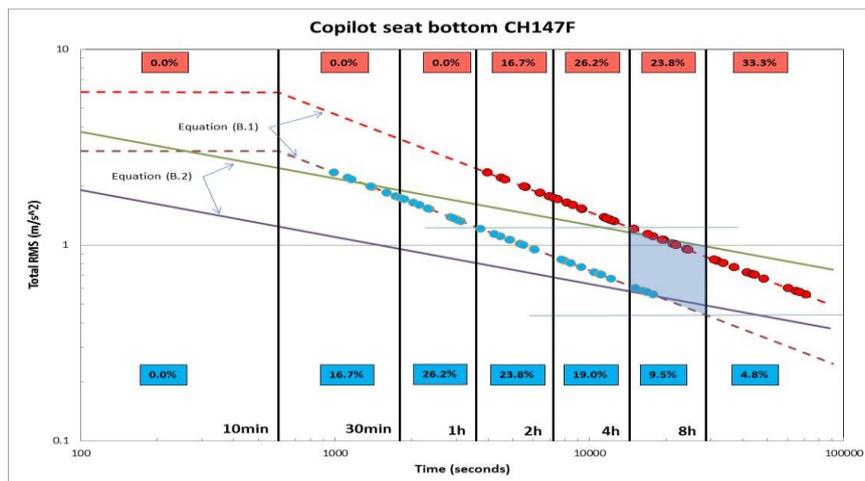


Figure 10: Estimated exposure time limit for each flight condition

Since there was no standard flight mission profile available for the CH-147F helicopter, the pilot weighted vibration levels in the 42 flight conditions were mathematically averaged to provide an approximate estimate for preliminary evaluation of the occupant whole-body vibration exposure in the CH-147F helicopter cabin. The average of weighted vibration levels was 1.19 m/s² in terms of health risk evaluation. Referencing to the “Vibration Health Risk Guideline Caution Zone” defined in

ISO2631-1:1997, the suggested maximum exposure time for the tested flight profile was between 1.0 and 3.3 hours depending on the lower and upper limit respectively. In terms of “Comfort and Perception” guidelines, the averaged vibration level was 1.15m/s^2 , which was qualitatively rated as “Uncomfortable”.

Based on the weighted rms vibration levels and referencing to the “Vibration Health Risk Guideline Caution Zone” recommended by ISO2631-1:1997, the maximum continuous daily exposure time has been calculated for each flight condition using the vibration equivalent equation listed in Appendix B of the standard, and the results are shown in Figure 10. Since there is no standard mission profile available for a military helicopter, the measured aircrew weighted whole-body vibration levels in representative flight conditions can be used as reference indexes to determine the helicopter aircrew whole-body vibration exposure in real flight missions using the following equation (ISO2631-1, B.1)

$$a_{w1} \times T_1^{1/2} = a_{w2} \times T_2^{1/2}$$

where a_{w1} and a_{w2} are the weighted rms acceleration for the first and second exposure respectively, and T_1 and T_2 are the corresponding exposure duration for the first and second exposure.

3.4. Aircrew vibration survey

In addition to the quantitative measurement of aircrew whole-body vibration levels, a questionnaire survey was also performed to evaluate the aircrew’s subjective perception on the localized postural discomfort in the CH-147F Chinook helicopter. The survey was performed using two copies of a questionnaire form: one copy was completed by the aircrew before the flight, and the other copy was completed immediately after the flight test.

In each questionnaire form, the aircrew were requested to rate their subjective perception on the discomfort at various locations on a voluntary basis. The rating was suggested between 0 and 10, where 0 indicated “no discomfort at all” and 10 indicated “extreme discomfort”. An example of the form is shown in Figure 11. The locations of greatest interest included the occupant neck, shoulder, lumbar back, bottom and thigh.

Before the flight, the pilot reported “very little discomfort” (level 1 out of 10) at the neck, right shoulder, left and right lumbar spine, and no discomfort at other locations. After the 100 minutes flight test, the pilot reported increased level of discomfort (level 2 out of 10) at the neck, both sides of shoulders and the lumbar locations. Notably, the pilot also reported an increased level of discomfort at the bottom and thigh locations (level 2 out of 10). However, the level reported was identified as “little discomfort” and below “moderate discomfort”.

Compared to the pilot, occupants in other locations also reported “moderate discomfort” (level 3 out of 10) at the neck, should, lumbar and bottom locations and “high discomfort” (level 5 out of 10) at the thigh location.

It is interesting and important to note that the subjective ratings from the pilot seem to be somewhat less severe than analytically measured results. Specifically, as shown in Figure 9, the data for the pilot correlated to conditions of “uncomfortable” in 30 of 42 flight profiles, “very uncomfortable” in 9 of the 42 flight profiles and “extremely uncomfortable” in 3 of 42 flight conditions, although the qualitative

assessment by the pilot in the survey did not identify any conditions that were either “moderate” or “high” discomfort. Except the difference in individual tolerance to vibration, another possibility for this discrepancy was the relatively short duration (100 minutes) of this flight mission. Also noted in the ISO2631-1997 standard, the occupant reactions at various magnitudes in public transport platforms depend on passenger expectations with regards to trip duration and the type of activities passengers expect to accomplish such as reading, writings etc. and many other factors such as noise and temperature etc.

Localised Postural Discomfort

0	no discomfort at all
0.5	extremely little discomfort (hardly noticeable)
1	very little discomfort
2	little discomfort
3	moderate discomfort
4	somewhat high discomfort
5	high discomfort
6	
7	very high discomfort
8	
9	
10	extreme discomfort (almost maximum)

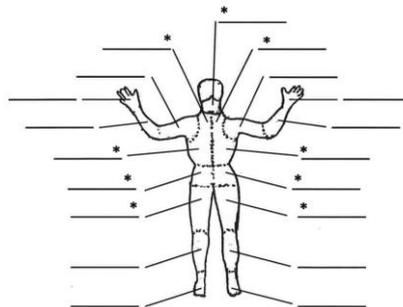


Figure 11: Localized postural discomfort survey form used in CH-147F flight test

Despite the fact that the questionnaire that reflected subjective perception of the qualitative results by the occupants after a relatively short flight mission, the whole-body vibration data did show that the pilot was exposed to high whole-body vibration levels under the tested flight conditions that may adversely affect his short-term comfort and perception. According to the quantitative vibration data, the high whole-body vibration levels measured during the CH-147F helicopter test flights may also have an adverse impact on long term health and well-being should actual CH147F missions have a similar flight spectrum, especially with consideration of the long flight duration the aircrew experience in combat missions.

4. Conclusion

This paper presented an evaluation of the pilot whole-body vibration exposure levels in specific flight conditions of the CH-147F Chinook helicopter. The following observations have been obtained based on the flight test results.

1. The pilot whole-body vibration occurred at the N/rev harmonic frequencies of the tandem rotor speed, and the amplitude was dominantly related to the 3/rev and 6/rev harmonics.
2. The weighted vibration levels varied significantly with flight conditions and load configurations. High levels of whole-body vibration existed in high speed level flights and manoeuvres above 120 kts, and the worst flight conditions occurred at 150 kts level flight conditions. These flight conditions were rated as “Extremely Uncomfortable” in terms of ISO comfort and perception guidelines.

3. Comparing the vibration spectra at the helicopter floor and the seat bottom interface for the pilot, vibration levels were found to be amplified through the seat in the low frequency range up to 12/rev (45 Hz).
4. Referencing to ISO2631-1:1997, the preliminary linear averaged whole-body vibration level of the pilot was rated as “Uncomfortable”, and the suggested maximum exposure time for the tested flight profile should be between 1.0 and 3.3 hours referencing to the “Vibration Health Risk Guideline Caution Zone”.
5. Compared to flight speed, the status of the payload door on the helicopter (opened or closed in flight) did not affect the pilot whole-body vibration significantly.
6. There appeared to be differences in the subjective analysis by the pilot compared to the analytical results measured during flight. Individual tolerance to vibration and the short flight duration were possible explanations. However, the reasons for this difference are not completely apparent in this study, and should be investigated throughout the fleet and a representative complement of pilots.

5. Acknowledgement

The authors would like to acknowledge the support from the Directorate of Technical Airworthiness and Engineering Support (DTAES) - Human Factors Engineering of the Department of National Defence of Canada and RCAF 450 THS squadron staff. The assistance from Heather Wright, Brent Lawrie and Camile Lebrun, and the Airworthiness Group of the NRC Flight Research Laboratory is also appreciated.

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