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Seat Vibration in Military Propeller Aircraft: Characterization, Exposure Assessment, and Mitigation

Suzanne D. Smith

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There have been increasing reports of annoyance, fatigue, and even neck and back pain during prolonged operation of military propeller aircraft, where persistent multi-axis vibration occurs at higher frequencies beyond human whole-body resonance. This paper characterizes and assesses the higher frequency vibration transmitted to the occupants onboard four aircraft: the WC-130J, C-130J, C-130H3, and E-2C.

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Seat Vibration in Military Propeller Aircraft: Characterization, Exposure Assessment, and Mitigation

Suzanne D. Smith

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Introduction: There have been increasing reports of annoyance, fatigue, and even neck and back pain during prolonged operation of military propeller aircraft, where persistent multi-axis vibration occurs at higher frequencies beyond human whole-body resonance. This paper characterizes and assesses the higher frequency vibration transmitted to the occupants onboard these aircraft. *Methods:* Multi-axis accelerations were measured at the occupied seating surfaces onboard the WC/C-130J, C-130H3, and E-2C Hawkeye. The effects of the vibration were assessed in accordance with current international guidelines (ISO 2631-1:1997). The relative psychophysical effects of the frequency components and the effects of selected mitigation strategies were also investigated. *Results:* The accelerations associated with the blade passage frequency measured on the passenger seat pans located on the side of the fuselage near the propeller plane of the C-130J (102 Hz) and C-130H3 (68 Hz) were noteworthy (5.19 ± 1.72 ms^{-2} rms and 7.65 ± 0.71 ms^{-2} rms, respectively, in the lateral direction of the aircraft). The psychophysical results indicated that the higher frequency component would dominate the side passengers' perception of the vibration. Balancing the props significantly reduced the lower frequency propeller rotation vibration (17 Hz), but had little effect on the blade passage frequency vibration. *Conclusions:* The relationships among the frequency, vibration direction, and seat measurement sites were complex, challenging the development of seating systems and mitigation strategies. Psychophysical metrics could provide a tool for optimizing mitigation strategies, but the current international vibration standard may not provide optimum assessment methods for evaluating higher frequency operational exposures.
Keywords: whole-body vibration, aircraft vibration, back pain, discomfort.

EXCESSIVE NOISE AND vibration have historically been associated with military propeller aircraft. While noise protection devices have been and continue to be designed to reduce any adverse effects of prolonged exposure to noise, the effects of human vibration exposure on occupant comfort, fatigue, and even health have not been a high priority issue. More recently, targeted reports of annoyance, fatigue, and even symptoms of back pain associated with vibration have received more serious attention. In several cases, the reports were precipitated as a result of modifications or upgrades to an aircraft and the potential for even longer exposure durations due to the demands of current national and international affairs. In one case, human vibration exposure became an issue due to relocation of key crewmembers. In the WC-130J Weatherbird, the Dropsonde Officer was moved from the rear of the cabin or cargo bay to a position on the right side of the aircraft cabin located in close proximity to the propeller plane. Likewise, the Aerial Reconnaissance Weather Officer (ARWO) was moved from a position on the flight deck or cockpit to a position in the cabin located on the left side of the aircraft in close proximity to the propeller plane. Both crewmembers complained of annoying vibration that they felt would contribute to increased fatigue and reduced performance during long missions. The incident with the WC-130J also raised questions about the vibration exposure in the C-130J variant of the aircraft used for transporting troops and/or cargo. One example where health effects have been suggested during prolonged flight is onboard the U.S. Navy E-2C Hawkeye. The Navy conducted a survey of 185 Early Warning aviators (42% pilots/copilots and 58% Naval Flight Officers or NFOs) onboard the E-2C Hawkeye that had undergone a propulsion upgrade. The results indicated that 80% of the respondents had experienced neck and/or back pain in a 1-yr period (5). The majority of these individuals indicated that the pain lasted for at least 1 to 2 d. Approximately 35% of those reporting pain considered the symptoms a limiting factor in job performance.

The Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HE), has conducted several operational studies to characterize and assess the vibration transmitted to the seated occupants onboard propeller aircraft. These aircraft include the four-engine, six-bladed WC-130J and C-130J (8); the four-engine, four-bladed C-130H3; and the two-engine, four-bladed E-2C Hawkeye (9). This paper presents and compares the results of these studies, emphasizing the higher frequency vibration that occurs beyond 10 Hz and above human whole-body resonance. The vibration is specifically associated with the rotor speed or propeller

rotation frequency (PRF) and blade passage frequency (BPF) of these aircraft. The health risk and comfort reaction of the vibration exposures were assessed in accordance with the current international standard (3). This investigation includes the analyses of the relative psychophysical effects of the higher frequency components and the effects of selected mitigation strategies on reducing the vibration in propeller aircraft.

METHODS

The studies conducted onboard the WC/C-130J and C-130H3 were exempted from review by an Institutional Review Board since the participants were crewmembers or study participants performing their normal duties in accordance with approved test plans. The study conducted onboard the E-2C Hawkeye was approved by the Committee for the Protection of Human Subjects, Naval Health Research Center, San Diego, CA. An equipment flight clearance was obtained from the Naval Air Systems Command. The cabin crew included those occupants who performed specific tasks during a mission (WC-130J ARWO and the E-2C NFOs). Passengers were defined as troops who were being transported and not required to perform tasks (C-130J and C-130H3).

Measurement Equipment and Instrumentation

Two remote vibration environment recorders were used to collect simultaneous accelerations on each aircraft. Each 16-channel data acquisition unit (DAU) measured approximately 16.5 cm × 10 cm × 4 cm. The DAU enclosure was fabricated using Delrin® and T6-6061 aluminum and provided electromagnetic interference shielding. Two types of battery packs supplied power. The first was rated at 12 V/2.1 amp-hours and measured approximately 5 cm × 9 cm × 3 cm. The second was rated at 12 V/3.5 amp-hours and measured approximately 7 cm × 9 cm × 3 cm. Two batteries could be connected to each DAU to provide continuous operation from 2 to 5 h. Triaxial accelerometer packs and pads were used to measure accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions (relative to the seated occupant). The packs were comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin® cylinder. The packs measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 g (25 g with connecting cable). Triaxial accelerometer pads were used to measure the vibration at the seat/occupant interfaces. These pads provided an estimate of the vibration entering the occupant in accordance with ISO 2631-1:1997 (3). Each pad consisted of a flat rubber disk approximately 20 cm in diameter and weighing 355 g (with connecting cable). Embedded in the disk was a triaxial accelerometer pack (described above). The accelerometer packs and pads were attached using double-sided adhesive tape. Duct tape was also used to secure the pads. A triggering device measuring 7.6 cm in length and 2.2 cm in diameter with a weight of 20 g was used to initiate the collection of acceleration time histories for a predetermined time duration.

Acceleration Measurements and Flight Configurations

For the WC-130J, C-130J, and C-130H3, measurements were made at the copilot location on the flight deck (right side). A triaxial accelerometer pack was attached at the seat base. Another was mounted onto the top of the seat pan cushion (seat pan) to measure the accelerations entering the occupant. In the cabin area of the WC-130J, measurements were made at the ARWO location in the vicinity of the propeller plane on the left side. A triaxial accelerometer pack was attached at the seat base. This site was located at the front of the seat and above the adjustment mechanisms for moving the seat in the fore-and-aft (X) and lateral (Y) directions. Two accelerometer pads were mounted onto the seat pan cushion (seat pan) and seat back cushion (seat back), respectively. In the C-130J and C-130H3, the passengers were also located in the vicinity of the propeller plane. One triaxial accelerometer pack was attached on the floor at the location of the left side passenger. In the C-130J, the pack was mounted onto a rigid horizontal beam attached to the floor and located beneath the passenger seat. In the C-130H3, the pack was mounted on the floor directly in front of the seat. The differences in the sites were due to restrictions introduced by the storage of other equipment beneath the C-130H3 passenger seat. A triaxial accelerometer pad was mounted directly onto the cloth seat pan of the left side passenger seat in both the C-130J and C-130H3. These side passenger (troop) seats were mounted onto the side of the fuselage. For the C-130J, measurements were also made at the floor and on a passenger seat pan along the centerline of the aircraft near the propeller plane. None of the passenger seats included any cushioning material. An investigator from the AFRL/HE collected all C-130 measurements. This individual was also the left side passenger in the C-130J and C-130H3 and weighed approximately 61 kg. The center passenger in the C-130J weighed approximately 95 kg.

For the E-2C Hawkeye, the occupants carried the DAU on the inside pocket of a survival vest. Accelerations were measured at the three NFO locations in the cabin area aft of the propeller plane on the right side of the aircraft. The Radar Officer (RO) was located at the front of the cabin area. The Air Control Officer (ACO) was located at the rear of the cabin area, while the Combat Information Center officer (CICO) was located between the RO and ACO (9). Measurements at the copilot location were not included in the analysis due to sensor damage (9). At each location, a triaxial accelerometer pack was attached to the seat base on the lower rear right side of the relatively rigid seat frame, which was attached to an adjustment mechanism for translating and rotating the seat. Two accelerometer pads were attached between the occupant and the seat at the seat pan and at the seat back, respectively, similar to the arrangement in the WC-130J.

Prior to each flight, a portable computer was used to balance all accelerometers and arm the DAUs. During this process, the triggering device was set to collect acceleration time history segments for 30 s onboard the WC/C-130J, and for 20 s onboard the C-130H3 and E-2C Hawkeye. Multiple time history segments could

TABLE I. AIRCRAFT FLIGHT CONFIGURATIONS.

Aircraft	Altitude	Speed	Condition	Location
WC-130J	18,000 ft	180 KIAS*	Props as is	Copilot
	24,000 ft	220 KIAS	Props balanced	ARWO
		MCP**		
C-130J	18,000 ft	180 KIAS*		Copilot
	24,000 ft	220 KIAS		Center passenger
		MCP**	Props balanced	Port-side passenger
C-130H3	16,000 ft	240–300 KIAS	Props balanced	Copilot
	24,000 ft			Port-side passenger
E-2C	15,000 ft	220–250 KIAS	Cruise	RO, ACO, CICO
		≈160 KIAS	Loiter	

*Data used in one-third octave band analysis only.
**Maximum continuous power.
KIAS = knots indicated air speed; ARWO = Aerial Reconnaissance Weather Officer; RO = Radar Officer; ACO = Air Control Officer; CICO = Combat Information Center Officer.

be collected during the flight. All data were low-pass filtered at 250 Hz using a six-pole Butterworth filter and digitized at 1024 samples · s^{-1}.

Table I lists details on the flight configurations for the data selected for analysis and comparison among the aircraft. The flight configurations were restricted to relatively level flight at altitudes ranging between 15,000 and 24,000 ft and speeds ranging between approximately 160 and 300 knots indicated air speed (KIAS). Two flights were conducted on the WC-130J, one for each prop condition (Table I). One flight was conducted on the C-130J. Two flights were conducted on the C-130H3. Three flights were conducted on the E-2C. During Flight 1, data were collected at the RO and ACO locations. During Flight 2, data were collected at the CICO and ACO locations. During Flight 3, data were collected at the RO location. The same individual triggered the data collection for all three flights.

Data Processing

Each data channel represented in the time history data segment was processed to estimate the constant bandwidth power spectral density using the Matlab® signal processing toolbox (The MathWorks, Inc., Natick, MA). Welch's method (10) was used to divide the signal into 2-s sub-segments with 50% overlap. A Hamming window was then applied to these segments, and the resultant power spectral densities were averaged for each 30- or 20-s period. The constant bandwidth rms acceleration levels were calculated from the following relationship:

$$a_{rms_i} = \sqrt{(a_{psd_i}{}^*0.5)}$$
Eq. 1

where i represents the ith frequency component and 0.5 is the frequency resolution in Hertz (Hz).

The acceleration time history segments were also analyzed in one-third octave proportional frequency bands using a software program developed by Couvreur (1). The program uses Matlab® routines to generate the rms acceleration level in each one-third octave band (reported at the center frequency) in each direc-

tion. The program was modified to include frequencies below 25 Hz.

Data Analysis

The constant bandwidth rms accelerations at the PRF and BPF of each aircraft were evaluated. For the locations onboard the WC-130J and C-130J, the acceleration levels at both altitudes and for 220 KIAS and maximum continuous power (MCP) were combined and averaged for the props as-is and props balanced conditions, respectively (from eight processed time history segments each). It should be noted that, in some cases, MCP was at 220 KIAS. For the locations onboard the C-130H3, the acceleration levels at the 2 altitudes were combined and averaged (from 14 processed time history segments). For the E-2C, the acceleration levels at all NFO locations were averaged for each condition since the preliminary analysis did not show a definitive effect of occupant location (8) (from 23 processed time history segments for cruise and 17 processed time history segments for loiter).

For evaluating the operational exposures in accordance with ISO 2631-1:1997, the one-third octave data for the WC/C-130J at 180 KIAS was also included with the one-third octave data associated with 220 KIAS and MCP (from four additional processed time history segments). **Table II** lists the frequency weightings and multiplying factors representing equal human sensitivity for assessing both health risk and comfort reaction. In this study, the weighted overall rms acceleration level (a$_w$) at the seat pan and seat back in each axis (X, Y, and Z) was calculated over a selected frequency range as:

$$a_w = \left[\sum_i w_{j}^2 a^2 rms_i \right]^{1/2}$$
· Eq. 2

where j represents the particular frequency weighting (Table II), and i represents the ith frequency component (at the center frequency of the one-third octave frequency band). For the C-130H3 and E-2C, the frequency range was 1 to 80 Hz as recommended in ISO 2631-1:

TABLE II. FREQUENCY WEIGHTINGS AND MULTIPLYING FACTORS (ISO 2631-1:1997).

| | Health Risk | | Comfort Reaction | | | |
| | Seat Pan | | Seat Pan | | Seat Back | |
Direction	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X	Wd	k = 1.4	Wd	k = 1.0	Wc	k = 0.8
Y	Wd	k = 1.4	Wd	k = 1.0	Wd	k = 0.5
Z	Wk	k = 1.0	Wk	k = 1.0	Wd	k = 0.4

1997. For the WC/C-130J, the frequency range was 1 to 100 Hz to include the BPF. Although a frequency weighting is given for the 100-Hz one-third octave band, the standard does not recommend exceeding 80 Hz. The vibration total value (VTV) at each measurement site was then calculated using the weighted overall acceleration levels:

$$VTV = \sqrt{k^2 a_{wx}^2 + k^2 a_{wy}^2 + k^2 a_{wz}^2}$$ Eq. 3

where a_{wx}, a_{wy}, and a_{wz} are the overall weighted rms accelerations measured at the seat pan or seat back in the X, Y, and Z directions, respectively, and k is a multiplying factor (Table II). For assessing health, guidance is given for vibration entering the body at the seat pan. The vibration total value for health (VTV$_H$) was compared with the health guidance caution zones given in Fig. B.1 of the standard (3). Health effects have not been indicated for vibration levels occurring below the lower boundary line depicted in Fig. B.1 of the standard. There is the potential for health risk between the lower and upper boundary lines. Health risks are likely above the upper boundary line. The assessment of comfort reaction was accomplished using the vibration total value for comfort (VTV$_c$) calculated at the seat pan and seat back. In addition, an overall VTV$_c$ was calculated as the root sum of squares of the VTVs calculated at the seat pan and seat back. Each VTV$_c$ was compared with the comfort reactions given in ISO 2631-1:1997. The reactions are based on those that are likely in public transport and are independent of time.

The coordinate system used for all figures is relative to the occupant and seat where X is from the back to the chest (fore-and-aft), Y is from the right side to the left side (lateral), and Z is from the buttocks to the head (vertical). The aircraft coordinate system was defined as follows: X is the longitudinal axis, Y is the lateral axis, and Z is the vertical axis. The ARWO (WC-130J) was oriented 180° from the horizontal coordinate axes of the aircraft (facing backwards). During flight, the E-2C NFOs were rotated 90° from the longitudinal axis of the aircraft. For comparison, the lateral (Y) occupant/seat direction for the ARWO corresponded to the fore-and-aft (X) direction for the NFOs (back to chest). Paired and unpaired t-tests were used to statistically compare selected data. Significant effects were defined as p < 0.05.

RESULTS

Aircraft Frequency Spectral Characteristics

Although low-frequency vibration (below 10 Hz) can occur during intermittent turbulence in propeller air-

craft, the occupants were constantly exposed to specific frequencies of vibration associated with the propulsion system. The constant bandwidth frequency spectra for the WC/C-130J and C-130H3 showed a consistent peak at 17 Hz that coincided with the PRF of these aircraft. The frequency spectra for the E-2C showed a consistent peak at 18.5 Hz that coincided with the PRF of the aircraft. Other peaks observed below 60 Hz appeared to be associated with harmonics of the PRF. The frequency spectra for all aircraft showed a prominent acceleration peak associated with the BPF (number of blades times the PRF). For the six-bladed WC/C-130J the peak occurred at 102 Hz. For the four-bladed C-130H3 the peak occurred at 68 Hz. For the four-bladed E-2C the peak occurred at 73.5 Hz.

Constant Bandwidth Analysis of rms Acceleration Levels

Fig. 1 illustrates the mean rms acceleration levels associated with the PRF (Fig. 1A) and BPF (Fig. 1B) for the cabin crew seat base, seat pan, and seat back, and for the cabin passenger floor and seat pan in each orthogonal axis (via stacked bar plots). At the PRF, Fig. 1A shows a reduction in the acceleration levels with the props balanced as compared with the props as-is in the WC-130J. The significance of this observation will be discussed later in the paper. For the E-2C, significantly lower fore-and-aft (X) acceleration levels occurred at the PRF during the cruise flight condition as compared with the loiter flight condition for all three measurement sites. Significantly higher vertical (Z) accelerations occurred at the PRF during the cruise flight condition as compared with the loiter flight condition at the seat pan and seat back. The lowest vibration associated with the PRF in both the WC-130J and E-2C aircraft occurred along the longitudinal (X) direction of the aircraft (WC-130J seat X direction and E-2C seat Y direction in Fig. 1A). While significant differences did occur among the seat measurement sites for both aircraft in the longitudinal direction, these effects are not presented due to the relatively low vibration levels. Along the lateral direction of the aircraft, the WC-130J showed significantly higher vibration levels at the PRF for the seat back as compared with the remaining two sites (seat base and seat pan) for both prop conditions (seat Y direction), while the E-2C showed a tendency for lower vibration levels at the seat back (seat X direction). Both the WC-130J and E-2C showed significantly lower vibration levels at the PRF for the seat pan in the Z direction regardless of the propeller or flight condition. As shown in Fig. 1A, the vibration levels at the PRF
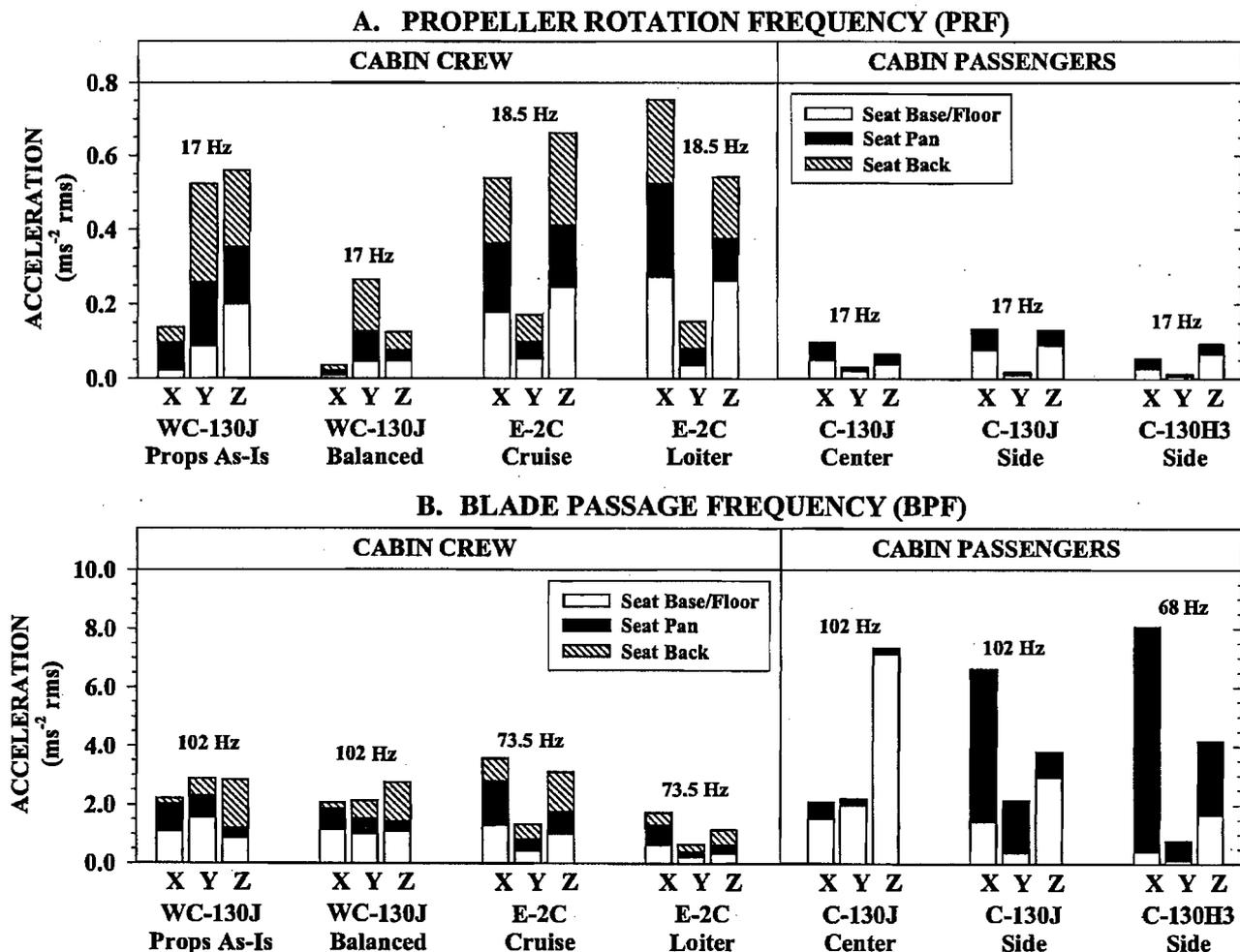
Fig. 1. Mean constant bandwidth rms acceleration levels of: A) propeller rotation frequency (PRF); and B) blade passage frequency (BPF).

appeared to be substantially higher in the E-2C (seat Y, X, and Z, respectively) as compared with the levels associated with the props balanced condition in the WC-130J (seat X, Y, and Z, respectively).

For the cabin passengers, the lowest acceleration levels associated with the PRF also occurred along the longitudinal axis of the aircraft (seat Y direction), with higher accelerations tending to occur in the YZ plane of the aircraft (seat X and Z directions) as observed for the WC-130J ARWO and E-2C NFOs. For both C-130J passengers, the seat pan vibration at the PRF was significantly lower as compared with the floor in the X seat direction. For the C-130H3 passenger, no significant differences were observed between the two seat sites in the X seat direction. All passengers showed significantly lower seat pan accelerations as compared with the floor in the Z direction. Of particular interest was the tendency for lower PRF acceleration levels in the X seat direction and possibly in the Z direction for the C-130H3 side passenger as compared with the C-130J side passenger, although large variations were observed in the C-130J. These differences may have been influenced by the location of the floor accelerometers as well as seat position relative to the propeller plane. It was speculated that there may have been a shift in

occupant location by one seat between the C-130J and C-130H3.

In contrast to the results at the PRF, balancing the props appeared to have little effect on the acceleration levels associated with the BPF in the WC-130J, and, depending on the seat measurement site, the vibration levels were not necessarily the lowest along the longitudinal axis of the aircraft. The E-2C did show the lowest levels of seat vibration at the BPF in the longitudinal direction of the aircraft, similar to the observations at the PRF. In contrast to the results at the PRF was the tendency for higher acceleration levels during E-2C cruise as compared with E-2C loiter in all three directions. The fore-and-aft (X) cabin crew seat back accelerations were significantly lower as compared with the seat base and seat pan at the BPF for both aircraft and all conditions. Fig. 1B shows that the differences were quite substantial. For the WC-130J, both the lateral (Y) seat back and lateral (Y) seat pan accelerations were also significantly lower as compared with the seat base. However, the WC-130J showed significantly lower vibration at the seat pan but significantly higher vibration at the seat back in the Z direction (Fig. 1B). The E-2C showed no differences in the vibration associated with the BPF at the seat base or seat pan, but did show

significantly higher vibration at the seat back in the Z direction.

The relatively high floor accelerations but low seat pan accelerations associated with the BPF and observed at the C-130J center passenger as compared with the C-130J side passenger were of particular interest. This may have been influenced not only by the seat location and mechanism of seat attachment to the aircraft, but also by the differences in the weights of the passengers and seating posture. In both the longitudinal and lateral directions of the aircraft, both the C-130J and C-130H3 side passenger seat pan accelerations were significantly higher as compared with the respective floor accelerations. In particular, the accelerations associated with the BPF measured in the X direction at the side passenger seat pans in the C-130J and C-130H3 were quite notable (Fig. 1). Although the C-130H3 side passenger floor accelerations appeared to be lower as compared with the C-130J side passenger floor levels in the X direction, the C-130H3 seat pan accelerations appeared higher as compared with the C-130J side passenger in the X direction (recognizing that the BPF in the C-130H3 occurred at a lower frequency). In addition, both the C-130J center and side passengers showed significant and substantial reductions in the seat pan acceleration levels associated with the BPF as compared with the floor in the Z direction, but the opposite was observed for the C-130H3 passenger. These differences were quite dramatic and not easily explained by any differences in the location of the floor accelerometers or seat.

Health Risk and Comfort Assessments

Fig. 2A illustrates the health guidance caution zones given in ISO 2631-1:1997. Included in the figure are the highest VTVs (VTV$_H$) calculated for each aircraft for selected conditions and occupant locations. The values are plotted for exposure durations in the range of 1 min to 24 h. As shown in Fig. 2A, the majority of the highest levels observed for the VTV$_H$ fell at or below the lower boundary line during a 24-h exposure duration. The exceptions were the values calculated for the C-130H3 side passenger and E-2C NFOs during cruise. The highest VTV$_H$ for the C-130H3 crossed the lower boundary line between 2.5 and 3 h of exposure. This VTV$_H$ crossed the upper boundary line at about 10 h. According to the ISO 2631-1:1997 guidelines, exposure lasting over 10 h at the acceleration levels associated with this VTV$_H$ would most likely be a health risk for the occupant. During E-2C cruise, the highest VTV$_H$ crossed the lower boundary line at about 10 h, but never reached the upper boundary line by 24 h. In contrast, during E-2C loiter, the highest VTV$_H$ remained below the lower boundary line throughout the 24-h period.

It is cautioned that the VTV$_H$ values presented in Fig. 2A represent the worst-case exposures and do not necessarily reflect the flight scenarios for long-duration operations. For example, during a typical E-2C mission, the crew is exposed to both the cruise and loiter flight conditions. For a 4-h mission, it was estimated that the cruise flight condition lasted between 5 and 30 min, while the loiter flight condition lasted approximately 3 h and was associated with the actual mission task.

This would lower the VTV$_H$ and extend the exposure time where health risks have not been clearly documented. Although not shown, all of the lowest values for VTV$_H$ fell below the lower boundary line during a 24-h period with the exception of the lowest value for the C-130H3 side passenger. This VTV$_H$ crossed the lower boundary line between 10 and 15 h of exposure and remained between the boundary lines at 24 h. These results indicated that for the WC/C-130J and E-2C occupants located in the propeller plane, the actual VTV$_H$ representing level flight would most likely remain in the exposure region where health effects have not been clearly documented. For the C-130H3 side passenger located in the propeller plane, prolonged missions under the flight conditions evaluated in the study (Table I) may present the potential for health risks according to the guidelines given in ISO 2631-1: 1997.

Fig. 2B includes the mean vibration total values ± 1 SD for comfort (VTV$_C$) for each aircraft at selected conditions and occupant locations. For the WC-130J ARWO and E-2C NFOs, the VTV$_C$ for the seat back and the combined seat pan and seat back are included (overall VTV$_C$). For the WC-130J props as is, only 1 of the 12 data points showed a VTV$_C$ for the seat back and an overall VTV$_C$ that exceeded 0.315 ms^{-2} rms, indicating that the exposures were considered "a little uncomfortable" in accordance with ISO 2631-1:1997. All eight of the WC-130J and C-130J exposures with the props balanced were considered "not uncomfortable." In contrast, all but 1 of the 14 data points at the seat pan on the C-130H3 were considered "fairly uncomfortable" with a VTV$_C$ ranging between 0.5 and 0.8 ms^{-2} rms. The one point was considered "not uncomfortable" (< 0.315 ms^{-2}). For the E-2C NFO locations during cruise, 5 of the 23 data points showed a VTV$_C$ at the seat pan that was considered "a little uncomfortable" with none of the seat back values exceeding 0.315 ms^{-2} rms ("not uncomfortable"). However, seven of the overall VTV$_C$s were considered "a little uncomfortable." All of the E-2C exposures during loiter were evaluated as being "not uncomfortable" according to ISO 2631-1:1997.

Psychophysical Effects

The frequency weightings given in ISO 2631-1:1997 imply that frequency components with similar weighted acceleration levels would be equal with regard to human sensitivity. Based on this concept, statistical analysis indicated that one of the frequency components associated with the propulsion system dominated the perception of the vibration by the occupant. **Fig. 3** illustrates the mean weighted one-third octave band accelerations associated with the PRF and BPF in each direction for each aircraft at selected conditions and occupant locations (stacked bar plots). The frequency component showing a significantly higher weighted acceleration is annotated in the figure.

For the WC-130J with the props as is condition, the results indicated that the lower frequency associated with the PRF (16-Hz one-third octave frequency band) would dominate the perception of the vibration in the Y and Z directions. With the props balanced, the greater
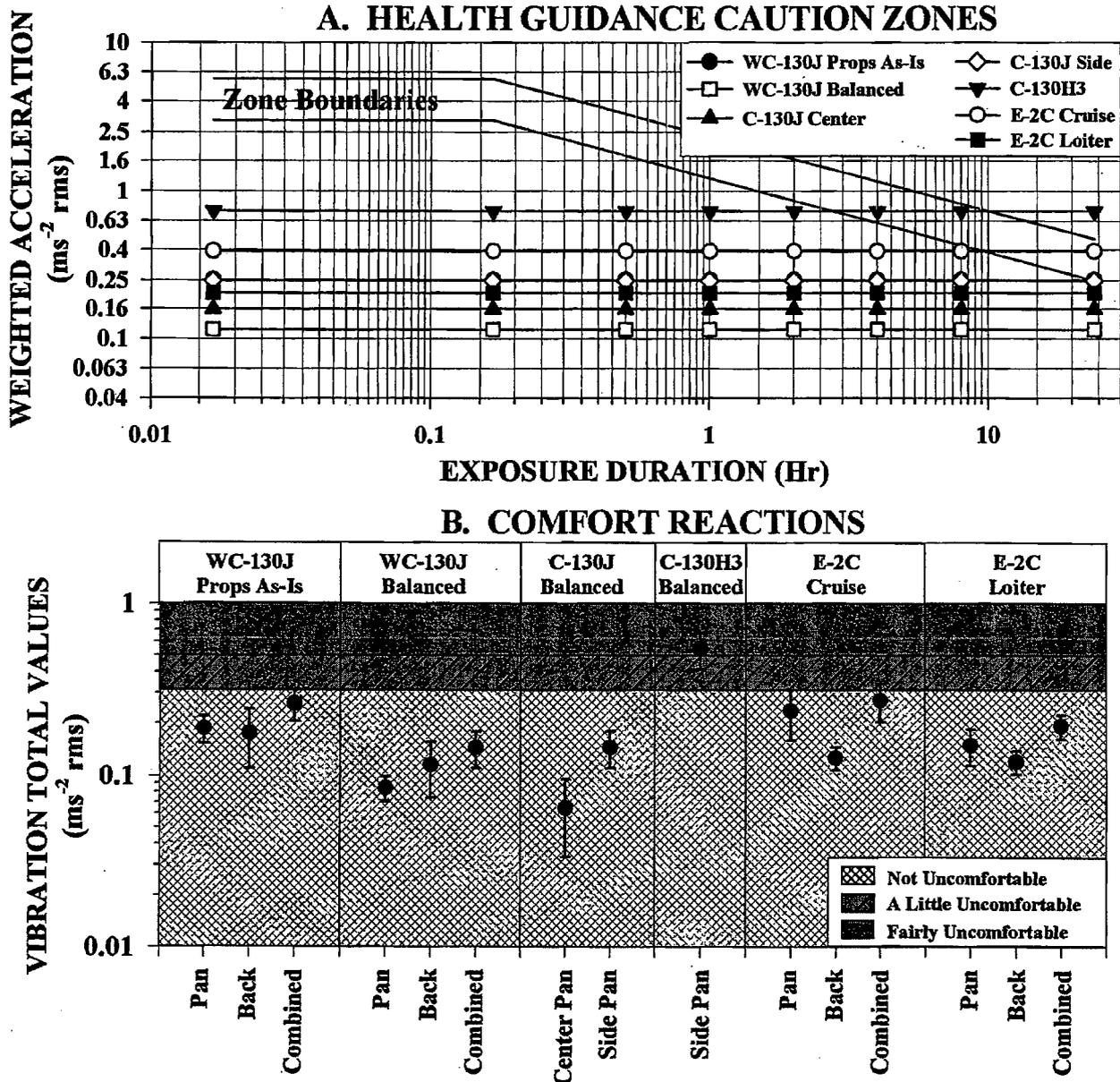
Fig. 2. Vibration total values (VTV) based on ISO 2631-1:1997 (3) of A) health guidance caution zones (VTVH); and B) comfort reactions (VTVc).

perception of the vibration associated with the PRF would be limited to the Y direction. This does coincide with a comment made by the ARWO that he noticed the higher frequency vibration more with the props balanced. For both the C-130J and C-130H3 side passengers, all directions showed that the BPF would have the greatest effect on the occupant perception of the aircraft vibration. Fig. 3 also suggests that the vibration occurring in the C-130H3 at the BPF (63-Hz one-third octave band) in the X and Z directions would be perceived as being more pronounced as compared with the vibration occurring in the C-130J at the BPF (100-Hz one-third octave band) in the X and Z directions. In both the horizontal and vertical directions, the ISO 2631-1:1997 frequency weightings show approximately a doubling of the vibration level in the 100-Hz one-third octave band for equal sensitivity to vibration in the 63-Hz

one-third octave band. However, the unweighted acceleration levels at the BPF shown in Fig. 1B were already higher in the C-130H3 as compared with the C-130J in the X and Z directions. For the E-2C, the frequency component that would have the greatest effect on occupant perception depended on the aircraft flight condition. The BPF was expected to have the greatest influence during cruise, while the PRF would have the greatest effect during loiter.

Vibration Mitigation

Fig. 4 illustrates the mean acceleration levels ± 1 SD at the PRF (17 Hz) in each direction in the WC-130J at the copilot seat pan and ARWO seat pan and seat back. The figure shows that balancing the props produced reductions in the WC-130J vibration occurring at the
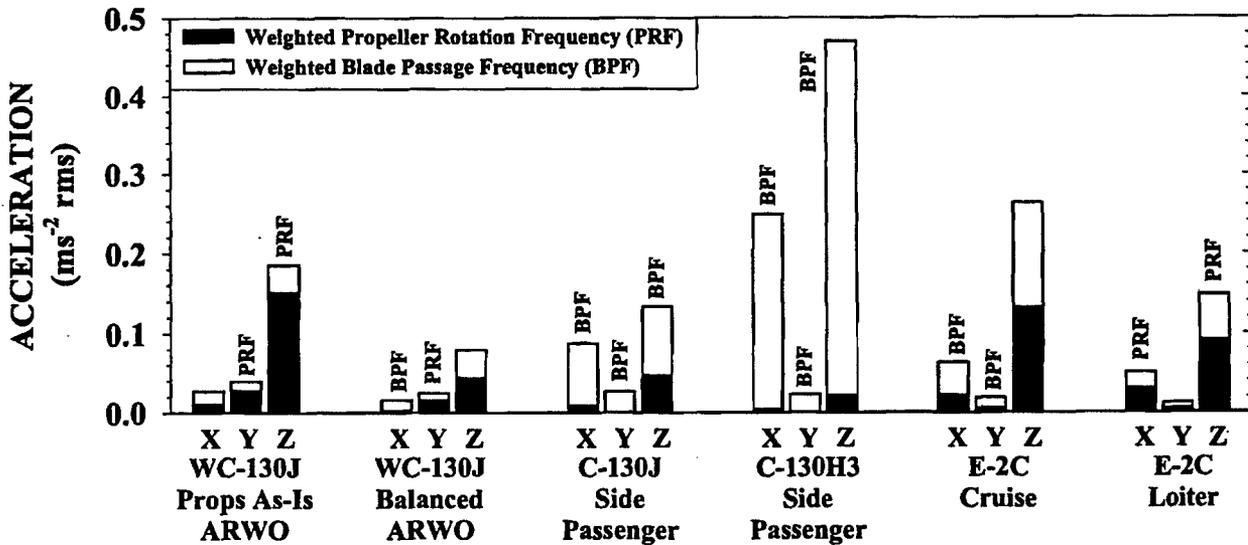
Fig. 3. Mean weighted seat pan accelerations at the propeller rotation frequency (PRF) and blade passage frequency (BPF) associated with the center-frequency of the one-third octave frequency band (PRF = 16 Hz in the C-130 variants and 20 Hz in the E-2C; BPF = 100 Hz in the WC/C-130J, 63 Hz in the C-130H3, and 80 Hz in the E-2C).

PRF (17 Hz). The reductions were significant at the copilot and ARWO seat base and seat pan and at the ARWO seat back in the X and Z directions (marked with an asterisk in Fig. 4). Although Fig. 4 suggests a tendency for a reduction in the vibration at 17 Hz in the Y direction for the higher levels observed at the ARWO seat pan and seat back, these differences were not statistically significant. The figure does show that large variations occurred in the Y-axis vibration levels for the ARWO. Although significant reductions were observed in the Y and Z directions at the ARWO seat base at the BPF (102 Hz) during data collection with the props balanced, there were no significant differences observed at the ARWO seat pan and seat back in any direction at 102 Hz for this prop condition.

DISCUSSION

This paper describes the vibration characteristics of several military propeller aircraft, emphasizing the higher frequency components associated with the PRF and BPF that are transmitted to the occupants. Vibration measured at the interface between the occupant and seating surface was used to assess the effects of the operational exposures on health and comfort in accordance with ISO 2631-1:1997. Based on the weighting curves and multipying factors given in Table II (3), only the side passenger in the C-130H3 showed any potential for health risk and discomfort based on the seat pan data alone. It is not known whether the vibration transmitted to the passenger through the seat back webbing
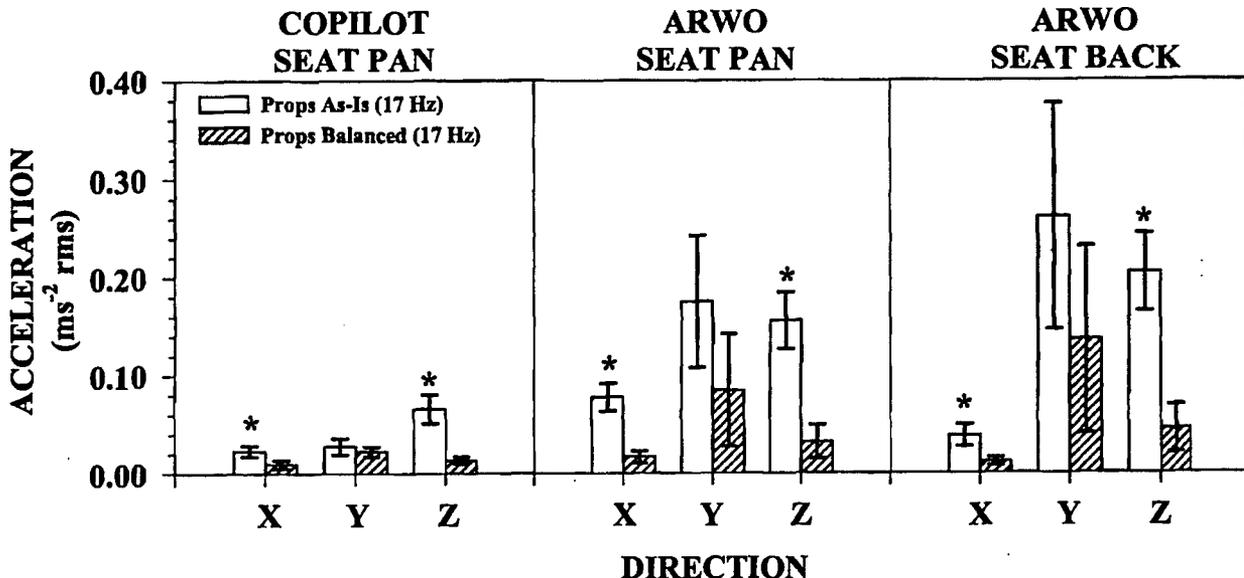

Fig. 4. Mean constant bandwidth rms acceleration levels at the propeller rotation frequency (17 Hz) ± 1 SD at selected measurement sites in the WC-130J aircraft. * indicates a significant reduction in the WC-130J vibration at the propellor rotation frequency (PRF) when the props were balanced.

could significantly affect the passenger comfort assessment on the C-130H3 or the C-130J, but the vibration would have been difficult to measure. The addition of the seat back vibration in the comfort assessment of the E-2C during cruise did affect the comfort reaction in two cases, but the majority of exposures were still considered "not uncomfortable." It is emphasized that the comfort reactions given in ISO 2631-1:1997 are based on public transport that is expected to be of short time durations and may not be applicable to prolonged exposures in military aircraft. The ISO 2631-1:1997 does provide alternative assessments, including the fourth power vibration dose method. This method calculates the vibration dose value (VDV) and is recommended where there are high crest factors (9 or greater), shocks, or transient vibration. Based on a preliminary analysis of selected data, the crest factors associated with level flight onboard the tested propeller aircraft were expected to be below 4. It is not clear whether the VDV method would have significantly affected the assessments. The ISO 2631-1:1997 does not provide sufficient guidance on using the VDV to assess comfort, nor does it consider the effect of substantial multi-axis vibration. Regardless, some researchers have supported the use of the VDV as more effective for long-duration exposures (4) and the method should be further investigated in military aircraft.

Another issue of concern is that the current frequency weightings given in the ISO 2631-1:1997 may not reflect occupant sensitivity to the higher frequency vibration so predominant in military propeller aircraft. There is also the issue of the 102-Hz BPF that is felt by the occupants in the WC/C-130J but occurs beyond the recommended assessment range of 1 to 80 Hz. Historically, a limited number of studies have developed sensitivity curves that included the 100-Hz frequency band and beyond (2,6,7). In summary, the current ISO 2631-1:1997 standard does not provide optimum assessment methods or guidelines for evaluating the higher frequency vibration exposures associated with military propeller aircraft.

Reducing the vibration at its source can be the most effective, but not always the most practical, mitigation strategy. The dramatic effect of dynamically balancing the propellers was seen in the WC-130J (Fig. 4). This practice is highly recommended for reducing vibration at the PRF in the C-130 aircraft variants. It is not known whether this practice exists for the E-2C Hawkeye. Given the relatively high levels of vibration observed in the E-2C, such a practice may be beneficial to the crew.

Another approach for reducing human vibration is to mitigate the motions at the location where they actually enter the body, i.e., the seating system. For the side passenger in the C-130J and C-130H3, it appeared that the direct attachment of the seating system to the fuselage of the aircraft contributed to the substantial vibration measured at the seat pan in the lateral direction of the aircraft. Mitigation strategies that focus on the seating system should consider the feasibility of using alternative mounting designs for the passenger (or troop)

seats. Seat cushions, where feasible, might be used to mitigate higher frequency vibration in the crewmember seats and are being investigated in this laboratory.

The characteristics of the E-2C mission provide another example of the difficulty in determining appropriate seat design and mitigation strategies. The two flight conditions showed differing effects at the PRF as compared with the BPF as shown in Figs. 1A and 1B. Specifically, during loiter it would be advantageous to use cushions that could effectively dampen the vibration at the PRF (given the relatively high levels observed in Fig. 1A and the psychophysical effects noted in Fig. 3). On the other hand, in considering the complexity of psychophysical effects and other factors that contribute to discomfort and back pain, a cushion that at least provides improvement in comfort and seating posture may have a positive effect on the E-2C crew.

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