ORIGINAL RESEARCH

Characterizing the Effects of Airborne Vibration on Human Body Vibration Response

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Background: Exposure to high intensity, low frequency noise can cause whole-body vibration. Such exposures to airborne vibration can reach the limits of human tolerance and have been associated with physiological and pathological disorders. The objective of this study was to characterize human body vibration response during exposures to operational airborne vibration. ***Methods:*** Triaxial body accelerations were collected at multiple anatomical sites with the subject located at selected crew positions during ground-based engine runup tests on several military tactical aircraft. The acceleration time histories were processed in one-third octave frequency bands and compared with the one-third octave band noise data. ***Results:*** The most significant finding was the occurrence of a resonance peak in the fore-and-aft (X) chest acceleration in the frequency bands between 63 and 100 Hz. Both the chest acceleration and associated noise level increased as the subject moved aft of the exhaust outlet, coinciding with the report of increasing chest vibration. A relatively linear relationship was found between the overall chest accelerations and noise levels between 5 and 250 Hz. An approach to developing combined noise and vibration exposure criteria was proposed. ***Conclusions:*** The resonance observed in the upper torso strongly suggested that airborne vibration in the 60 to 100 Hz frequency band may be an important contributing factor in the generation of subjective symptoms and possibly physiological and pathological disorders. Additional field and laboratory studies are required to validate the relationship between the biodynamic responses, noise levels, and physiological and pathological consequences.

Keywords: aircraft noise, whole-body vibration, human tolerance, vibroacoustic disease.

BOTH CIVILIAN AND MILITARY vehicles can expose the occupants to whole-body vibration that has been associated with human discomfort, performance degradation, and possible risks to health. Historically, the emphasis of human whole-body vibration research and the development of exposure criteria have focused on structure-borne exposures typically occurring from contact of the body with the vehicle floor or seating system. However, aircraft ground operations and maintenance crews can also be exposed to whole-body vibration via the airborne transmission of acoustical energy in the form of sound pressure waves. It is known that high performance aircraft produce high noise levels and, therefore, substantial levels of airborne vibration. The mismatch between the acoustic impedance of air and the human body surfaces prevents significant amounts of acoustical energy from entering the body, particularly at higher frequencies (14). With decreasing frequencies below 1000 Hz, more acoustical energy is absorbed in the form of transverse shear waves. With exposure to high intensity noise levels (120 dB SPL) between 100 and 1000 Hz, tissue vibration occurs and the noise is felt via the stimulation of somatic mechanoreceptors (6). Below 100 Hz, intense airborne vibration can cause whole-body vibration that not only affects motion in the chest, abdominal wall, viscera, limbs, and head, but can generate motions in the body cavities and air-filled or gas-filled spaces (6). Resonance of the chest wall and air-filled lungs has been reported to occur around 60 Hz based on model predictions and limited data (6,13,15).

One of the few studies that has evaluated the effects of whole-body exposures to high intensity noise, particularly with respect to human tolerance, was conducted by the Air Force in the 1960's (12). Several facilities were used for the study to obtain a frequency range of 1 to 100 Hz at sufficient noise levels ranging from 100 to over 150 dB. The study found that, for exposures below 150 dB, the most common symptom reported was mild to moderate chest vibration. From 50 to 100 Hz, pure tone exposures reached levels above 150 dB. Voluntary tolerance was reached at 50 Hz (153 dB), 60 Hz (154 dB), 73 Hz (150 dB), and 100 Hz (153 dB) based on the significance of symptoms reported by the subjects. These symptoms included mild nausea, giddiness, subcostal discomfort, cutaneous flushing and tingling (around 100 Hz); coughing, severe substernal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort, and giddiness (60 Hz and 73 Hz); and headache (50 Hz). All subjects reported significant fatigue following the exposures. The researchers did conclude that individuals experienced with noise environments and wearing hearing protection could tolerate airborne vibration below 50 Hz at noise levels up to 150 dB for short durations (2 min) without compromising safety. The results did indicate that exposures at higher frequencies (50 to 100 Hz) at these levels may be approaching the voluntary

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tolerance limits and could affect personnel performance.

More recently, Castelo-Branco and Alves-Pereira, 1999 (4) have published a collection of clinical, epidemiological, and laboratory studies on Vibroacoustic Disease (VAD). VAD is the "clinical manifestation of a systemic disease that develops after long-term exposure to noise (≥10 yr) which is characterized by large pressure amplitude (≥90 dB SPL) within the lower frequency bands (≤500 Hz) (LPALF)" (3). The collection provides extensive data on the pathological consequences associated with exposures to LPALF, particularly to the cardio-respiratory system. Their descriptions of the pathological consequences and the subjective symptoms reported in the Air Force study (12) suggest a strong correlation between the biodynamic stress associated with whole-body airborne vibration and the generation of pathology associated with VAD.

The conclusions of the study by Mohr et al., 1965 (12) are reflected in the current Air Force Occupational, Safety, and Health Standard AFOSHSTD 48–19 (2), which includes a section on whole-body vibration effects. The exposure criteria are based on the noise level. The standard recommends that no octave or one-third octave band noise level may exceed 145 dB for frequencies in the range of 1 to 40,000 Hz, and that the overall A-weighted sound pressure level must be below 150 dB(A). There were no time limits for exposures below these levels. However, the literature on VAD defines a lower noise level limit (90 dB) and the dependence of pathological symptoms on the length of exposure.

In contrast to the current airborne vibration exposure criteria, exposure criteria for whole-body vibration generated by contact with a supporting surface are based on the acceleration levels measured at the interface between the supporting surface and the body (the feet of the standing person, the buttocks, back, and feet of a seated person, or the supporting surface of a recumbent person) (7). Whole-body vibration exposure criteria are also time-dependent. The increased levels of exposure that are expected to occur with newer aircraft engine designs warrant a more thorough evaluation and understanding of the effects of airborne vibration on the human body, particularly the biodynamic effects. The objective of this study was to characterize the biodynamic human body vibration response occurring during exposures to airborne vibration caused by aircraft noise. A sub-objective was to develop a method for measuring human body accelerations in the operational environment. The approach was to measure noise and vibration on human subjects at multiple body locations and personnel positions during high-powered, ground-based engine runup tests on high performance military aircraft. The data collected on several aircraft will establish a baseline for the comparison and assessment of airborne vibration generated by the new Joint Strike Fighter (JSF) aircraft and will also contribute to the expansion of human exposure criteria for ground operation and maintenance personnel.

METHODS

Test Aircraft

The aircraft selected for the ground-based engine runup tests included the EA-6B Prowler powered by two Pratt & Whitney J52–408A engines (tail number 160434), the F-14A Tomcat powered by two Pratt &Whitney TF-30P-414A turbofan engines (tail number 160658), the F/A-18C Hornet powered by two General Electric F404-GE-402 turbofan engines (tail number 165402), and the F/A-18F Super Hornet powered by two General Electric F414-GE-400 turbofan engines (tail number unknown). The acoustical noise field was also measured for these aircraft. Detailed results for the noise measurements are reported under separate cover (8–11). Noise and vibration data were collected on the EA-6B and F-14A at Patuxent River Naval Air Station, Patuxent, MD. Additional noise data were collected on the F/A-18C aircraft in May, 1998 along with the human body acceleration data at Patuxent River Naval Air Station. The F/A-18F test was conducted at Lakehurst Naval Air Station, NJ. The F/A-18F noise data presented in this paper were collected 2 d after the collection of the human body acceleration data under similar testing conditions. The weather at Patuxent River was mild, with temperatures ranging from 40–60 °F, light winds, and relatively low humidity. At Lakehurst, the air temperature was similar but the winds were high during the collection of vibration data.

Equipment

The lightweight, portable vibration measurement system called REVER (Remote Vibration Environment Recorder) (EME Corporation, Annapolis, MD) used to collect the body vibration accelerations included a 16-channel digital data acquisition unit (DAU) measuring approximately 16.5 cm x 10 cm x 4 cm. The system was powered by a battery pack measuring approximately 5 cm x 9 cm x 3 cm and allowing up to 2 h of operation. The combined DAU and battery weighed approximately 1.4 kg and were carried by the subject in either a fanny pack or survival vest. Flexible, lightweight cables connected the DAU to a series of triaxial accelerometer packs used to measure body accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions. The accelerometer packs consisted of three miniature accelerometers (Entran EGA-125-10D, Entran Devices, Inc., Fairfield, NJ) enclosed in a Delrin disk measuring 1.9 cm in diameter and 0.86 cm in height. One accelerometer pack weighed approximately 5 g. Calibration of the accelerometers showed that those used in the study were relatively flat up to about 250 Hz. In addition, the subject stood on a thin rubber disk measuring 20.3 cm in diameter. The disk contained 3 orthogonally arranged miniature accelerometers (Entran EGA-125-10D, Entran Devices, Inc., Fairfield, NJ) and was used to measure the accelerations at the interface between the subject and ground. The disk and cable weighed 940 g. A hand-held trigger device was used to collect multiple segments of data based on initiation by the subject. A laptop computer was used to initialize and arm the system. Once armed, the laptop was removed from the

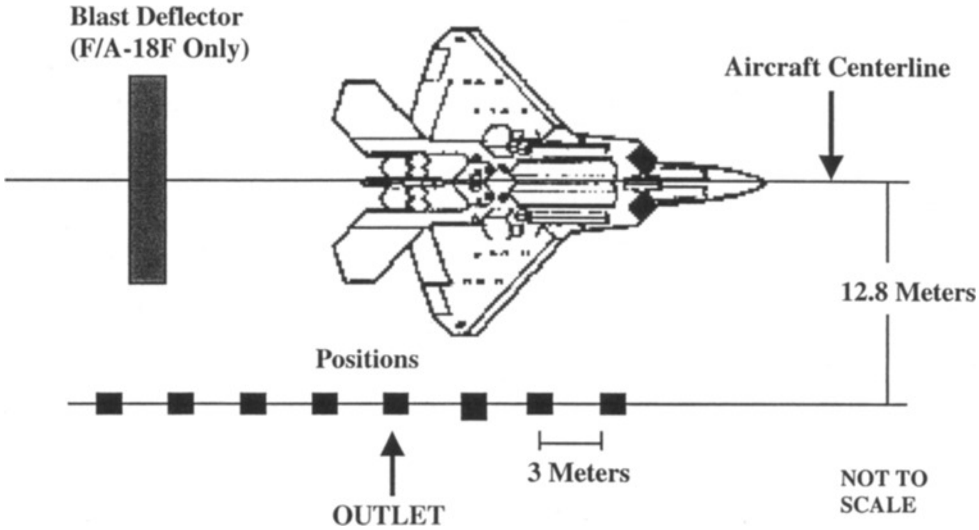

Fig. 1. Noise and vibration measurement positions.

area. Due to the limited availability of equipment for measuring human vibration response in the field, one subject was used to collect all acceleration data. The subject was a female with a weight of approximately 61.2 kg. The subject wore loose cotton denim trousers and shirt in addition to the fanny pack or survival vest containing the DAU.

Procedures

Fig. 1 illustrates the subject positions relative to the aircraft where body accelerations and noise were measured. For all tested aircraft, measurements were made at positions located along a line parallel to and 12.8 m from the longitudinal centerline of the aircraft. The subject was positioned along this line at 3-m increments. At each increment, data were collected while the subject maintained an upright posture facing the aircraft. For the F/A-18C, data were also collected at the approximate site where the final checker was positioned during catapult takeoff.

A catapult holdback was used to restrain the aircraft during the engine runups. For the EA-6B, measurements were made at military power (MP). For the F-14A and F/A-18C, power settings included both military power and afterburner (AB). The power setting for the F/A-18F was afterburner only. In addition, a jet blast deflector was used with the F/A-18F. **Table I** lists the subject positions and power settings for each aircraft. The subject positions are reported in 3-m increments either forward or aft of the aircraft exhaust outlet.

The triaxial accelerometer packs were attached to the subject's head (using a bitebar), chest (at the manubrium), lower thoracic spine, and lower leg using double-sided adhesive tape. At each subject position, acceleration data were collected for 10 s. For the majority of aircraft, data were low-pass filtered at 250 Hz (anti-aliasing) using a 6-pole Butterworth filter and digitized at 1024 samples per second. For the F/A-18C and F/A-18F, data were low-pass filtered at 600 Hz and sampled at 2048 Hz. Data were evaluated only up to 250 Hz.

Sound pressure levels (noise levels) were recorded simultaneously at each 3-m position at the two power settings (except for the EA-6B and F/A-18F as described above). The sound pressure levels were evaluated in one-third octave frequency bands between 5 and 16,000 Hz and reported in decibels at each center frequency. The overall noise level (in dB) and the weighted noise level [dB(A)] were also reported (8–11).

The acceleration time histories were analyzed in one-third octave bands using a software program developed by Couvreur (5). The program used MATLAB (The Mathworks, Inc., Natick, MA) routines to generate the root-mean-square (rms) acceleration level for each one-third octave band (reported at the center frequency) (1,7). The program was modified to include frequencies below 25 Hz. For initial comparison to the acceleration data (reported in g_{rms}), the one-third octave acoustical noise spectra reported in decibels (dB) were converted to sound pressure levels in units of Pascals using the following relationship:

$$1 \text{ dB} = 20 \log(p/p_0) \qquad \text{Eq. 1}$$

where p is the measured sound pressure in Pascals (Pa) and p_0 is the reference sound pressure equal to 2.0×10^{-5} Pa. The overall acceleration at each anatomical site for each position was calculated as follows:

$$a_{Overall} = \left[\sum_i (a_i)^2 \right]^{1/2} \qquad \text{Eq. 2}$$

TABLE I. SUBJECT POSITIONS AND POWER SETTINGS.

	Aircraft					
	EA-6B	F-14A		F/A-18C		F/A-18F
Position	MP	MP	AB	MP	AB	AB
9 m For*			X	X	X	X
6 m For		X	X	X	X	X
3 m For	X	X	X	X	X	X
Outlet	X	X	X	X	X	X
3 m Aft	X	X	X	X	X	
6 m Aft	X	X	X	X	X	
9 m Aft	X			X	X	
12 m Aft				X	X	
Final Checker					X	

* Forward.

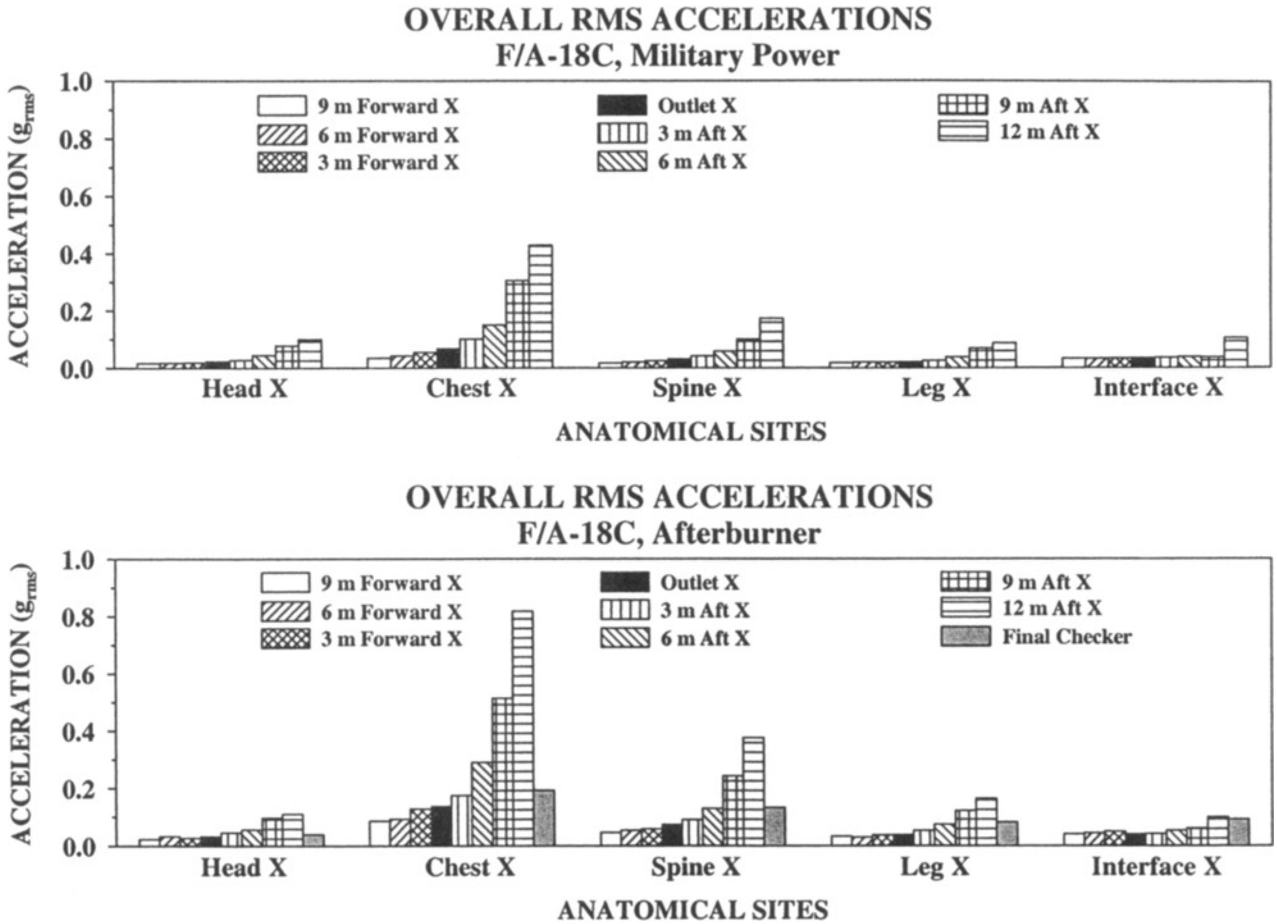

Fig. 2. Overall rms accelerations for the F/A-18C exposures at military power and afterburner.

where a_i is the acceleration level at the ith one-third octave frequency band. The overall noise levels were originally calculated between the one-third octave frequency bands of 5 to 16,000 Hz (frequency band numbers 7 to 42). In order to compare the overall body accelerations and noise levels, the overall noise levels for each position were also calculated for the frequency range of 5 to 250 Hz in units of Pascals and decibels. Eq. 2 was applied to the data in Pascals. For decibels, the following equation was used:

$$dB_{Overall} = 10 \log\left[\sum_i 10^{(SPL_i/10)}\right] \qquad \text{Eq. 3}$$

where SPL_i is the sound pressure level (in dB) at the ith one-third octave frequency band.

RESULTS

The highest body accelerations were observed in the fore-and-aft (X) direction. **Fig. 2** illustrates the overall fore-and-aft (X) body accelerations between 5 and 250 Hz at each position and at both power settings for the F/A-18C aircraft. The results shown for the F/A-18C were representative of the results for all of the aircraft with the exception of the F/A-18F. Measurements on the F/A-18F were limited to positions at the outlet and forward of the outlet due to the excessive heat generated by the jet blast deflector. Fig. 2 shows that the lowest body accelerations occurred for the lower body including the legs and ground interface. The highest accelerations occurred in the fore-and-aft (X) chest motion. The overall body accelerations tended to increase as the subject moved aft of the outlet. In addition, the overall levels tended to be higher during the afterburner exposures. The effect of position and power setting were the most dramatic for the fore-and-aft (X) chest motions. **Fig. 3** illustrates the one-third octave fore-and-aft (X) chest acceleration measured at the outlet and at 6 m aft of the outlet for all tested aircraft and power settings. The figure also includes the one-third octave vertical (Z) chest accelerations and the one-third octave sound pressure levels (noise levels) in units of Pascals. As represented by the chest accelerations shown in Fig. 3, the majority of body accelerations showed levels below 0.025 g_{rms} up to 40 Hz as reported at the center frequency of the respective one-third octave band. These low acceleration levels coincided with the relatively low noise levels (Pascals) occurring in this frequency range at both power settings for all tested aircraft. The exception was the response to the F/A-18F exposure at the outlet where relatively larger body accelerations were observed below 40 Hz. At about 40 Hz and above, the noise levels began to increase with increasing frequency as illustrated in Fig. 3. The body accelerations showed similar tendencies for increases in intensity with frequency, but the magnitudes of the

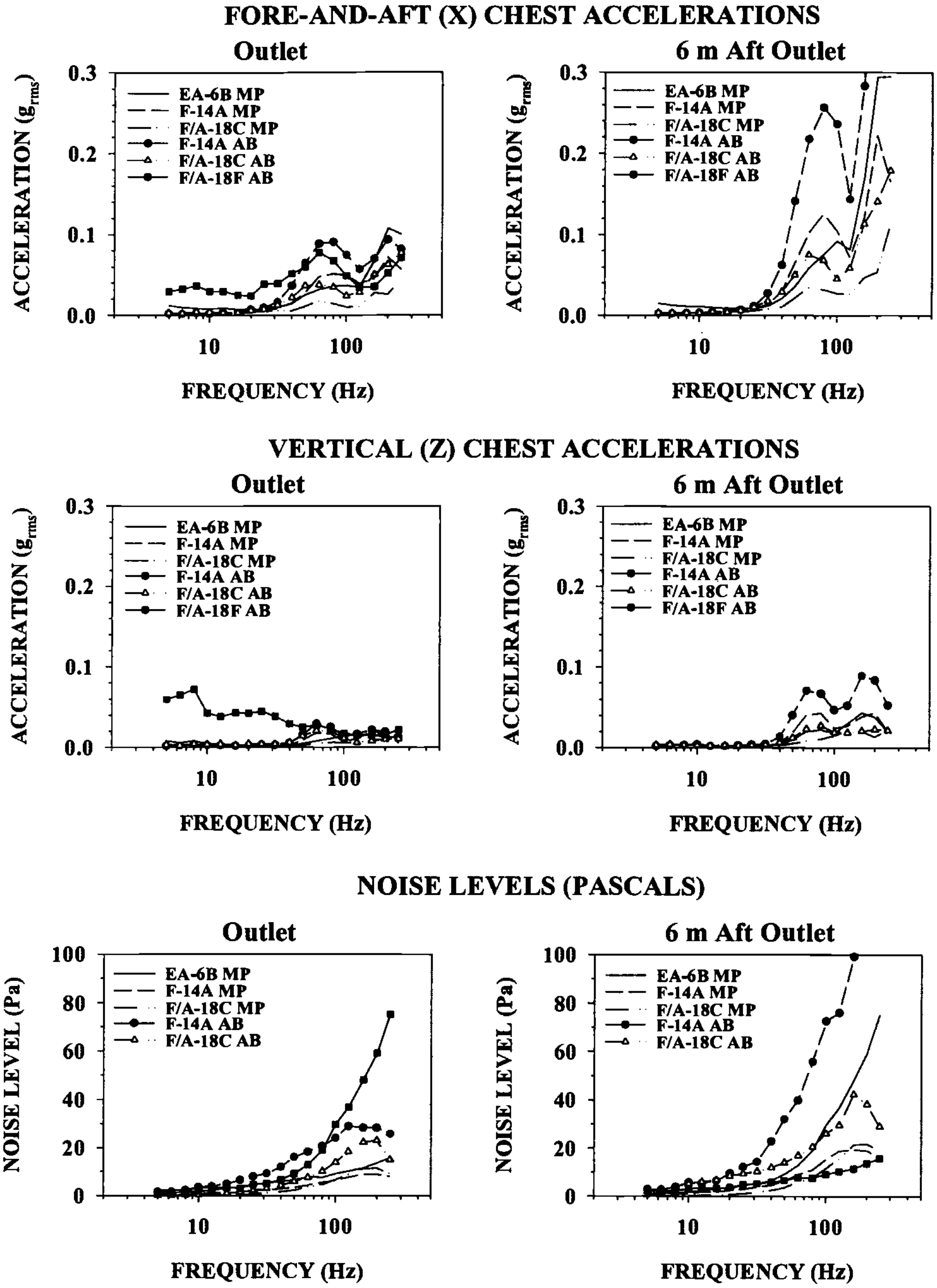

Fig. 3. One-third octave fore-and-aft (X) and vertical (Z) chest accelerations and noise levels.

accelerations depended on the body measurement location, direction, and aircraft power setting. The most significant observation was the generation of a peak in the fore-and-aft (X) chest response in the 63 to 100 Hz frequency bands for all aircraft as illustrated in Fig. 3. The vertical (Z) chest accelerations also showed a peak in the same frequency range but at a lower acceleration level. As shown in the figure, these peaks were not evident in the noise levels as dramatically shown at 6 m aft of the outlet. Although not shown, both the head and spine showed some tendency for an increased response in this frequency range, but the acceleration levels were low. The chest X and chest Z acceleration peaks strongly suggested the presence of an upper torso resonance in this frequency range.

Tables II and **III** list the frequency location and magnitude of the peak chest X acceleration and the associated noise level (in dB and Pa units) at military power and afterburner, respectively, for each aircraft. The Tables and Fig. 3 show differences in the peak chest X acceleration as well as the noise levels among the tested aircraft. The peak chest response primarily occurred in the 63 and 80 Hz frequency bands. For the EA-6B aircraft exposures at military power, the peak occurred primarily in the 100 Hz frequency band. The Tables and Fig. 3 also show that both the peak chest X accelerations and associated noise levels increased as the subject moved aft of the outlet, and tended to be higher for the afterburner exposures. This is dramatically illustrated for the F-14A. Of particular interest were the reductions

TABLE II. PEAK FORE-AND-AFT (X) CHEST ACCELERATIONS AT CENTER FREQUENCY OF ONE-THIRD OCTAVE BAND-MILITARY POWER.

	EA-6B			F-14A			F/A-18C		
Location	Freq (Hz)	Accel (grms)	SPL (Pa/dB)	Freq (Hz)	Accel (grms)	SPL (Pa/dB)	Freq (Hz)	Accel (grms)	SPL (Pa/dB)
9 m For*							80	0.008	2.296/101.2
6 m For				80	0.023	2.636/108.9	80	0.011	2.958/103.4
3 m For	63	0.026	7.015/110.8	80	0.032	3.281/109.9	63	0.014	2.698/102.6
Outlet	100	0.037	9.037/113.1	80	0.052	4.084/111.0	63	0.018	3.598/105.1
3 m Aft	100	0.052	7.692/111.7	80	0.088	5.508/112.9	63	0.026	4.426/106.9
6 m Aft	100	0.092	29.582/123.4	80	0.126	7.781/116.4	63	0.034	5.835/109.3
9 m Aft	100	0.158	68.554/130.7				80	0.060	13.063/116.3
12 m Aft							80	0.103	19.771/119.9

* Forward.

in the chest accelerations for the F-14A and F/A-18C at 6 and 9 m forward of the outlet, while the chest response remained relatively high at these positions in the F/A-18F (Table III). Although not shown, the relationship between the peak chest X acceleration and noise level was relatively linear for the tested aircraft with some exceptions.

Fig. 4 illustrates the overall fore-and-aft (X) chest accelerations for all tested aircraft at each position and power setting. Included in the figure are the overall noise levels (decibels) calculated for the two frequency ranges 5 to 16,000 Hz and 5 to 250 Hz. Fig. 4 shows that both the body accelerations and noise levels increased as the subject moved aft of the outlet for both power settings. Both levels also tended to be higher for the afterburner exposures. The overall chest X accelerations showed similar tendencies as compared with the peak one-third octave responses, although the F-14A exposures produced slightly higher peak accelerations as compared with the EA-6B at military power. It should be noted that the overall acceleration levels for the F/A-18F also included the relatively higher responses observed at lower frequencies (Fig. 3). Given the low acceleration levels observed at frequencies below the peak responses for the majority of the aircraft exposures, the overall body acceleration levels calculated between 5 and 250 Hz were, in general, reflective of the relative magnitudes of the resonance peaks occurring in the 63 to 100 Hz frequency bands.

Fig. 5 illustrates plots of the overall chest acceleration levels (5 to 250 Hz) vs. the overall noise levels in decibels (5 to 16,000 Hz). A relatively linear relationship between chest acceleration and noise level was observed when the chest acceleration levels in g_{rms} were plotted on a log scale as shown in Fig. 5a. In order to obtain a similar plot using a linear scale, the relationship $\log(a/a_0)$ was used, where a is the overall fore-and-aft (X) chest acceleration and a_0 is defined as the reference acceleration level for converting vibration acceleration to decibels. The level is equal to $1.0 \cdot 10^{-5}$ m $\cdot$ s^{-2} ($1.02 \cdot 10^{-7}$ g). This maintains a simple conversion to the measured overall chest accelerations while producing a relatively linear relationship between the chest response and the measured noise levels (Fig. 5b). In general, all of the aircraft appeared to have a similar linear relationship between the overall chest X acceleration and the overall noise level. However, Fig. 5 does show a distinct difference in the chest acceleration/noise relationship for the F-14A exposures at military power: higher overall acceleration levels occurring at lower noise levels as was also observed for the peak chest X responses. Linear regression analysis showed a correlation coefficient (R) of 0.671 when using the measurements for all tested aircraft. If the F-14A military power data were removed from the analysis, the correlation coefficient (R) improved to 0.887. The equations describing the linear relationships are given in Fig. 5. Fig. 4 shows that the characteristics of the overall noise levels were influenced by the frequency range (5–16,000 Hz vs. 5–250 Hz). It was expected that this would affect

TABLE III. PEAK FORE-AND-AFT (X) CHEST ACCELERATION AT CENTER FREQUENCY OF ONE-THIRD OCTAVE BAND-AFTERBURNER.

	F-14A			F/A-18C			F/A-18F		
Location	Freq (Hz)	Accel (grms)	SPL (Pa/dB)	Freq (Hz)	Accel (grms)	SPL (Pa/dB)	Freq (Hz)	Accel (grms)	SPL (Pa/dB)
9 m For*	80	0.025	12.051/115.6	63	0.027	4.529/107.1	80	0.069	48.532/127.7
6 m For	80	0.024	14.160/117.0	63	0.030	5.637/109.0	63	0.069	41.308/126.3
3 m For	63	0.078	13.063/116.3	63	0.041	6.040/109.6	63	0.077	42.759/126.3
Outlet	80	0.091	20.703/120.3	63	0.038	7.604/111.6	63	0.078	48.532/127.7
3 m Aft	80	0.149	32.065/124.1	63	0.058	9.796113.8			
6 m Aft	80	0.257	55.722/128.9	63	0.075	16.635/118.4			
9 m Aft				80	0.128	36.394/125.2			
12 m Aft				80	0.213	45.293/127.1			

* Forward.

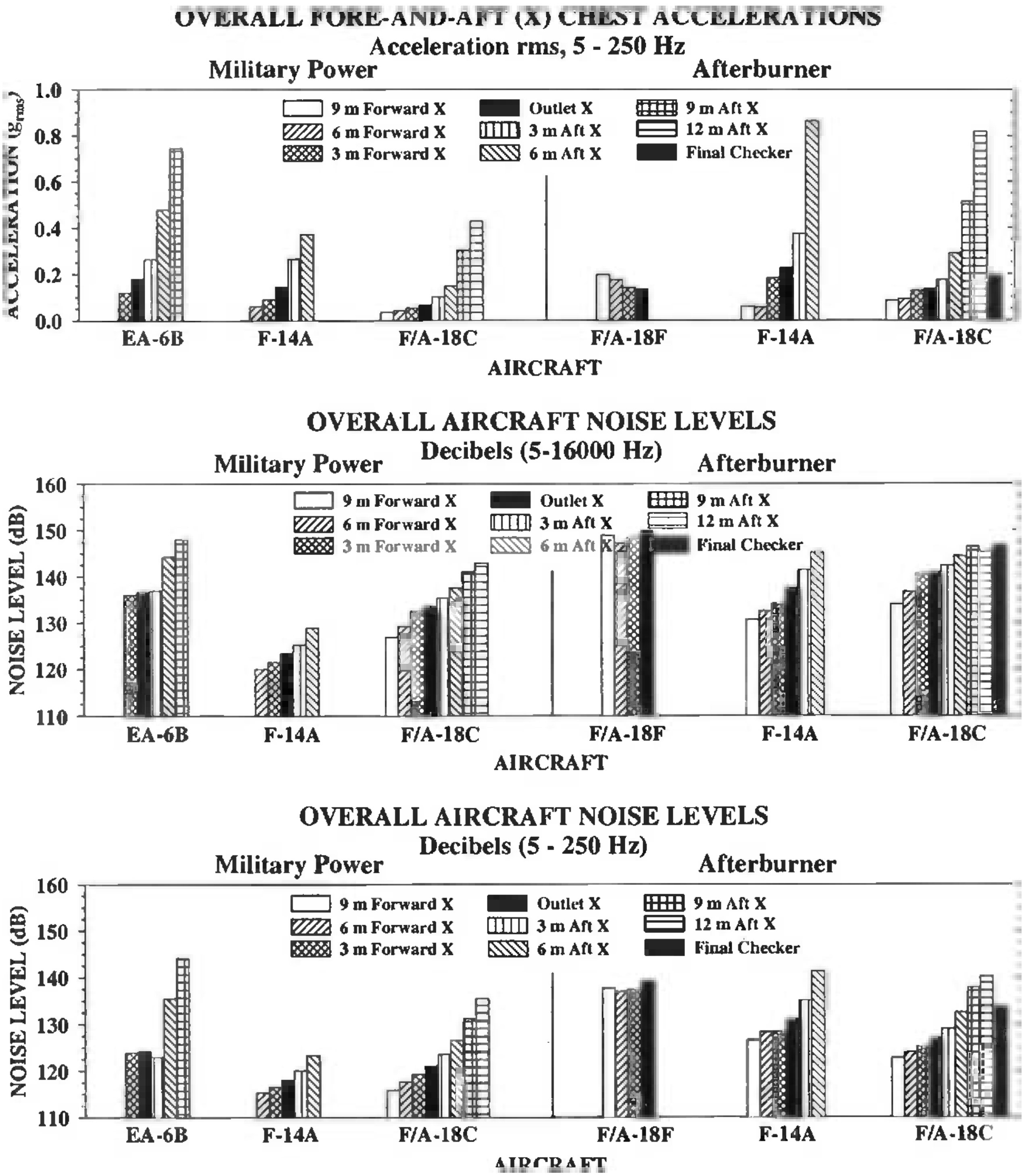

Fig. 4. Overall fore-and-aft (X) chest accelerations and overall noise levels for each aircraft at each tested position.

the relationship between the overall chest accelerations (evaluated between 5 and 250 Hz) and the overall noise levels. **Fig. 6** illustrates the plot of the overall chest accelerations [$\log(a/a_0)$] vs. the overall noise levels (dB) for the frequency range of 5 to 250 Hz. The data appear to be less scattered as compared with the plots shown in Fig. 5. The most dramatic difference was observed for the final checker position located forward of the outlet in the F/A-18C aircraft but inside the 12.8 m centerline. This position was closer to the aircraft but slightly forward of the outlet. Between 5 and 250 Hz, the overall noise level for the final checker position was around 134 dB. Higher frequency noise produced an overall noise level of 146.7 dB at this position for the frequency range of 5 to 16,000 Hz. The overall chest acceleration measured at the final checker position was relatively low at about 0.07 g_{rms} with the subject reporting primarily tolerable symptoms. For the frequency range of 5 to 250 Hz, the linear correlation coefficient (R) was increased to 0.819. Excluding the F-14A data at military power

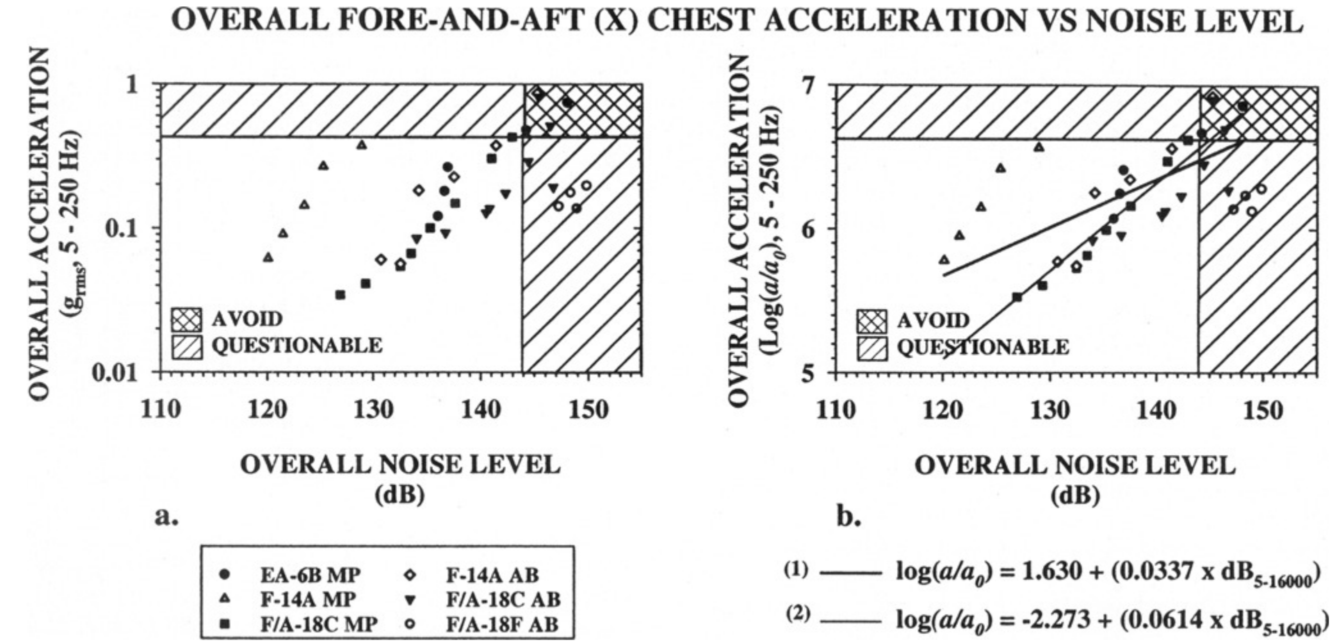

Fig. 5. Overall fore-and-aft (X) chest acceleration in a.) g_{rms}; and b.) Log(a/a_0) vs. overall noise level between 5 and 16,000 Hz. Fig. 5b includes linear regression plots with (1) and without (2) F-14A data at military power.

produced a slight increase in the R value to 0.907. The equation describing the relationship between the overall fore-and-aft (X) chest accelerations and noise levels is as follows:

$$\log(a/a_0) = 1.061 + (0.0406 \times dB_{5\text{-}250}) \qquad \text{Eq. 4}$$

where dB_{250} is the overall noise level between 5 and 250 Hz in decibels.

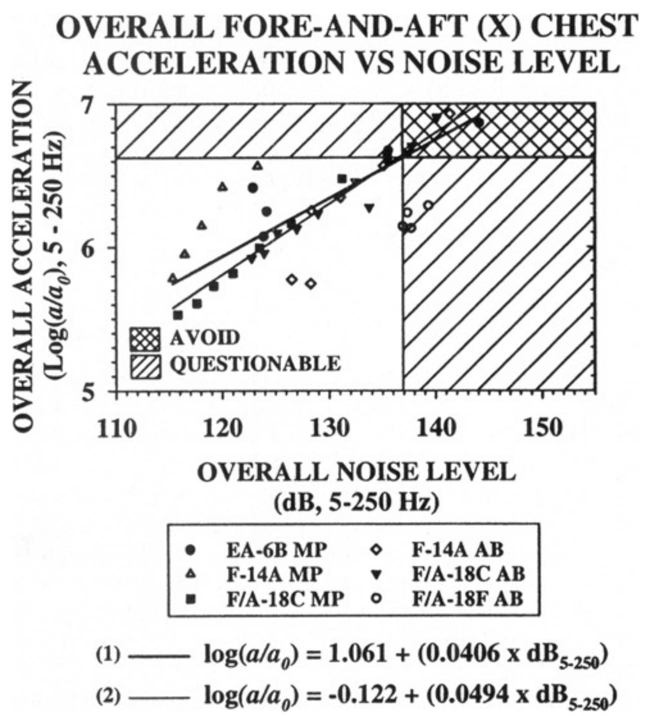

Fig. 6. Overall fore-and-aft (X) chest acceleration vs. overall noise level between 5 and 250 Hz. Figure includes linear regression plots with (1) and without (2) F-14A data at military power.

DISCUSSION

An important point should be raised about the interpretation of the body accelerations, particularly at the higher frequencies. Given the nature of the airborne vibration, the generated sound waves can excite the exposed accelerometer packs, the magnitude of the acceleration being partly dependent on the characteristics of the attachment surface. Therefore, the increases observed in the accelerations at the higher frequencies (particularly above 100 Hz) were not unexpected.

The most significant finding from this study was the occurrence of a peak acceleration response measured at the chest, with lower peaks also being observed at the head and spine in the 63 to 100 Hz frequency bands. The notable chest acceleration peaks observed in this study confirmed the previous reports of a chest (or upper torso) resonance in the vicinity of 60 Hz (6,13,15). The major symptom reported by the subject during the noise exposures was chest vibration, similar to the symptoms reported in the study by Mohr et al., 1965 (12). The subject noted that positions forward of the outlet were easily tolerated during the 10 to 20 s exposures at both power settings. The chest vibration increased in intensity as the subject moved farther aft of the outlet, coinciding with the increases observed in the fore-and-aft (X) chest accelerations.

During the measurement of body accelerations for the F/A-18F exposures, there were 30–40 kt wind gusts, which made it very difficult to maintain body stability. At the outlet position, there was also a substantial amount of heat blast from the deflector, as reported by the subject. There was a concern that these factors may have influenced the generation of the relatively larger acceleration levels recorded at lower frequencies at all body positions. The effects of the jet blast deflector on both noise and vibration should be further investigated.

In order to develop airborne vibration exposure criteria, it is desirable to use quantities that are typically measured and assessed in accordance with current standards. Overall levels are used in both human vibration and noise exposure assessments. The acceleration unit recommended for use in human vibration assessment is millimeters per second squared (related to g by a factor of 9.81 $m \cdot s^{-2}$ or the acceleration due to gravity). Sound pressure level in decibels is used in noise assessments. Given the relatively linear relationship observed between the overall fore-and-aft (X) chest acceleration and the noise level, an approach for developing airborne vibration exposure criteria based on both noise and vibration measurements was proposed. The first task was to determine the approximate acceleration levels and noise levels associated with minimal or low tolerance as described by the subject. The limiting levels occurred at 9 m aft of the outlet during the F/A-18C afterburner exposures. The overall chest acceleration was 0.513 g_{rms} and the associated noise level (5 to 250 Hz) was 137.8 dB. These limits include the F/A-18C at 12 m aft of the outlet, the F-14A full afterburner data at 6 m aft of the outlet, and the farthest position measured at military power for the EA-6B at 9 m aft of the outlet. It was decided to select a noise level limit of 137 dB (5 to 250 Hz), just slightly below the noise levels associated with minimal tolerance on the F/A-18C. Using Eq. 4, the $\log(a/a_0)$ was calculated to be 6.623. The associated acceleration level was 0.428 g_{rms}. These overall chest X acceleration and overall noise limits were used to define the hatched area shown in Fig. 6. For the data and subject symptoms observed in this study, this area represented an avoidance region for airborne vibration exposure. Questionable regions were also defined where either the noise limit of 137 dB (5 to 250 Hz) or the chest acceleration limit of 0.428 g_{rms} was exceeded. Fig. 6 shows that the EA-6B military power exposure at 9 m aft of the outlet falls just into the range for avoidance but does not meet the noise criteria. The figure also shows that the F/A-18F afterburner exposures fall in the avoidance region for noise but do not meet the chest acceleration criteria. It is expected that most noise assessors would generate an overall noise level based on assessing a higher frequency range (16,000 Hz in this study and 40,000 Hz as recommended by the AFOSHSTD 48–19) (2). An attempt was made to extrapolate the regions defined in Fig. 6 to the plots shown in Fig. 5. The overall chest acceleration limit did not change. In order to include the critical positions defining the avoidance region in Fig. 6, a minimum overall noise exposure of 144 dB was selected. It can be seen that the EA-6B military power exposure at 9 m has shifted into the avoidance region (Fig. 5). In addition, the final checker position and the position 3 m aft of the outlet for the F/A-18C during afterburner have exceeded this noise limit but not the chest acceleration limit.

It should be noted that, while the proposed approach does use the overall rms acceleration as described in ISO 2631–1: 1997(E) (7), the frequency range and weighting curves recommended by the standard were not used. ISO 2631–1: 1997(E) (8) recommends that the frequency range between 0.5 and 80 Hz be used for assessing the structure-borne vibration. However, the major airborne vibration effects may occur beyond this range. ISO weighting curves were designed to account for the sensitivity of the human body to structure-borne vibration below 10 Hz. Vibration components at higher frequencies are increasingly weighted. At 25 Hz, the measured acceleration is reduced by half; at 50 Hz, the weighted acceleration is 25% of the actual acceleration level. Likewise, it is common to report noise levels as A-weighted dB(A). The A-weighting is the best estimate of damage risk to hearing. It appears that both the vibration and noise weighting curves, and possibly the recommended frequency ranges, may not be relevant for determining the relationship between body acceleration and noise level during airborne vibration exposure.

None of the one-third octave noise levels exceeded 145 dB between 5 and 16,000 Hz (8–11). The noise levels associated with the one-third octave peak fore-and-aft (X) chest responses were all below 131 dB (Tables II and III). Fig. 4 further indicates that the exposures were below 150 dB(A) in accordance with the AFOSHSTD 48–19 (2), and below the 150 dB level associated with the limit of voluntary tolerance (12). It should be noted that AFOSHSTD 48–19 (2) includes the frequency range from 1 to 40,000 Hz. It is not clear at this time how tolerable the noise levels reported in this study would be among a larger subject population. It is expected that other subjects will show a chest resonance in the frequency range observed in this study. However, the magnitude of the peaks may vary depending on subject weight distribution, muscle tone, and stature. This may or may not affect the results shown in Figs. 5 and 6. In addition, the exposures in this study ranged from 10 to 20 s in duration. During daily operations, the duration may be shorter or longer, and may be intermittent. It may be possible to study the body accelerations, subjective response, and exposure duration for a larger subject pool in a controlled laboratory setting. The relationship between body biodynamics, noise levels, and long-term physiological and pathological consequences is critical for developing time-dependent airborne vibration exposure criteria.

CONCLUSIONS

1. Infrasound occurring at 40 Hz and below did not appear to be a problem for ground operation and maintenance personnel working with the tested aircraft.

2. A resonance was generated in the upper torso during exposure to aircraft noise during ground operations. In general, the magnitude of the associated peak fore-and-aft (X) chest response increased with the noise level. A relatively high linear relationship was found between the overall chest X acceleration levels evaluated between 5 and 250 Hz and the overall noise levels between 5 and 250 Hz. For higher frequency ranges (16,000 Hz center frequency), the relationship was less linear due to the characteristic noise distribution of a particular aircraft and also possibly due to position for a particular aircraft.

3. The results of this initial study into airborne vibration effects were used to propose an approach for developing airborne vibration exposure criteria. The development of exposure criteria based on this approach will require further study and expansion of the database on human body accelerations resulting from airborne vibration. A method for collecting subjective data will be required to quantify the subjects' symptoms and tolerance levels occurring during airborne vibration exposure.

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