



**A Comparison of Two Whole-Body Vibration Standards
as Applied to Rotary-Wing Aircraft:
ISO 2631 vs ADS 27**

By

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July 1988

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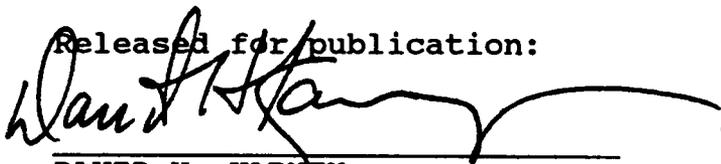


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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS NA		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Public release; distribution unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL 88-11			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory		6b. OFFICE SYMBOL (If applicable) SGRD-UAD-IV	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research and Development Command		
6c. ADDRESS (City, State, and ZIP Code) P. O. Box 577 Fort Rucker, AL 36362-5292			7b. ADDRESS (City, State, and ZIP Code) Fort Detrick, Frederick, MD 21701-5012		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.	
	62787A	3E162787A878	AD	132	
11. TITLE (Include Security Classification) A comparison of two whole-body vibration standards as applied to rotary-wing aircraft: ISO 2631 vs ADS-27 (U)					
12. PERSONAL AUTHOR(S) Dennis L. Breen and Barclay P. Butler					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 1988 July	15. PAGE COUNT 32
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	whole-body vibration, signatures, standards, health hazard assessment, comparison, ADS-27, ISO 2631, UH-60, UH-1		
20	11				
14	02				
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Two whole-body vibration (WBV) standards, International Standards Organization (ISO) 2631 and Aeronautical Design Standard 27 (ADS-27), were compared using vibration signatures from the UH-1 and UH-60 helicopters. ISO 2631 is a widely used WBV standard which accounts for variables such as intensity, duration of exposure, frequency range, and vibration in all three orthogonal directions. ADS-27 is a newer standard developed at the U.S. Army Aviation Systems Command (AVSCOM) for measuring WBV produced by rotary-winged aircraft. An analysis of the two vibration signature types shows when vibration levels are measured on a pass/fail performance criteria, the ADS-27 becomes the more stringent standard; however, ADS-27 fails to answer the important health hazard questions that ISO 2631 attempts. ISO 2631 vibration acquisition techniques were found to be more scientifically sound than those proposed by the ADS-27. The use of both standards may prove to be a more complete method of helicopter WBV assessment.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Chief, Scientific Information Center			22b. TELEPHONE (Include Area Code) (205) 255-6907	22c. OFFICE SYMBOL SGRD-UAX-SI	

Table of contents

	Page
List of figures.....	1
List of tables.....	2
Introduction.....	3
Methods.....	4
Data acquisition.....	4
Data analysis.....	7
ISO 2631 method of WBV analysis.....	9
ADS-27 method of WBV data analysis.....	11
Vibration transmission of seating system.....	18
Results.....	19
Discussion.....	21
Evaluation of the UH-60 WBV data.....	21
Evaluation of the UH-1 WBV data.....	21
Conclusions.....	23
References.....	24
List of equipment manufacturers.....	25

List of figures

Figure	Page
1. Triaxial accelerometers positioned to transmit vibration signals from seat pad location.....	5
2. Triaxial accelerometers positioned to transmit vibration signals from seat pan location.....	5
3. Triaxial accelerometers positioned to transmit vibration signals from floor location.....	6
4. Vibration data acquisition diagram.....	6
5. Data acquisition system.....	7
6. Data analysis diagram.....	9

List of figures (continued)

Figure	Page
7. ISO 2631 8-hour FDP curve limit, vertical axis....	10
8. ISO 2631 8-hour FDP curve limit, longitudinal and lateral axes.....	11
9a. UH-60 seat pad power spectrum: X-axis.....	12
9b. UH-60 seat pad power spectrum: Y-axis.....	12
9c. UH-60 seat pad power spectrum: Z-axis.....	13
10a. UH-1 seat pad power spectrum: X-axis.....	13
10b. UH-1 seat pad power spectrum: Y-axis.....	14
10c. UH-1 seat pad power spectrum: Z-axis.....	14
11. ADS-27 normalization curves.....	15
12. Intrusion index equation.....	16
13. Frequency response graph, UH-60, between pad and pan locations, Z-axis.....	18
14. Frequency response graph, UH-1, between pad and pan location, Z-axis.....	19

List of tables

Table	Page
1. Test conditions for UH-60 and UH-1.....	8
2. Intrusion index and 1BP frequency limits for flight regions 1 and 2.....	17
3. Percentage of acceptable WBV signatures.....	20
4. Average intrusion index.....	20

Introduction

There have been efforts to measure the degrading effects of whole-body vibration (WBV) on crewmembers of rotary-wing aircraft (Kidd, 1981). The various measurement and analytic techniques currently in use emphasize different aspects of the vibration signatures. However, an ideal technique used to assess the effects of WBV would need to be flexible enough to describe a great number of vibration signatures as well as provide a level indicator intended to determine vibration magnitudes that either present a health risk or act as a hindrance to normal flight performance. Such a technique also must indicate flight duration constraints for factors that include flight mission profiles, crewmember position, and types of aircraft. This report explores two standards that attempt to meet these goals, the International Organization of Standards 2631 (ISO 2631) and the Aeronautical Design Standard 27 (ADS-27).

ISO 2631 and ADS-27 present two different methods of measuring and interpreting the WBV produced by rotary-wing aircraft. ISO 2631 is a widely used WBV standard that can be adjusted for vibration measures on both ground vehicles and rotary-wing aircraft. ISO 2631 accounts for WBV variables such as intensity, duration, frequency, range and vibration in all three orthogonal directions (X, Y, Z axis), and relates these variables to conditions involving crewmember comfort, performance capabilities, and risk to health. Though it has been criticized (Osborne, 1983) for a lack of scientific foundation, ISO 2631 has been somewhat effective in quantifying the WBV levels experienced by the pilot, copilot, and crewmembers of Army helicopters.

ADS-27, a newer WBV standard developed at the U.S. Army Aviation Systems Command (AVSCOM), is applicable specifically to measures of WBV produced by rotary-wing aircraft. ADS-27 quantifies this WBV by obtaining a statistical measure of the harmonic peaks as seen in the power spectrum of a rotary-wing aircraft. An adequate comparison of ISO 2631 and ADS-27 would require that both standards set numeric limits above which the quantified WBV level produced is said to fail.

The objectives of this study were to determine the fundamental differences between WBV standards ISO 2631 and ADS-27 and to explore the usefulness of implementing both standards in future health hazard assessments (HHA) of Army rotary-wing aircraft.

Methods

Data acquisition

WBV signatures were collected from two different Army helicopter types: the UH-60, a twin-engined four-bladed system, and the UH-1, a single engine, two-bladed system. Triaxial accelerometers were positioned to transmit vibration signals from the following six locations: directly on top of the pilot and copilot seats (referred to as the "seat pad" locations) (Figure 1), hard-mounted to the underside of the pilot and copilot seats (referred to as the "seat pan" locations) (Figure 2), and hard-mounted to the helicopter frame directly beneath the pilot and copilot seats (referred to as the "floor" location) (Figure 3). The seat pad triaxial accelerometers (B & K model 4322*) were mounted in flat, flexible rubber disks approximately 12 inches in diameter, taped to that portion of the seat cushion in direct contact with the pilot or copilot and, therefore, measured vibration transferred directly from the helicopter seating system to the pilot or copilot. The seat pad location was specified by ISO 2631. The seat pan triaxial accelerometers (B & K model 4321*) measured the input vibration to the pilot or copilot seat cushion. Seat pan transducer locations were specified by ADS-27. Hard-mounted floor accelerometers (B & K model 4321) were used to pick up the helicopter frame vibration, or that vibration considered to be the input to the pilot and copilot seating systems.

Helicopter vibration signals in the X-, Y-, and Z-axis of motion are transmitted from the piezoelectric triaxial accelerometers*, amplified by Kistler model 5041BM01 charge amplifiers* and recorded on TEAC HR-30 portable analogue cassette recorders*. The TEAC HR-30 is a 7-channel record-only device with a frequency response range from 0.5 to 1250 Hz, limited by a tape recording speed of 4.8 cm/s. These recorders generate a frequency which compensates for noise in recorded signals. To allow for a proper signal-to-noise ratio, the portable recorders were set to an input range of ± 1 volt. One of the recorder channels was used as a voice monitor for documentation. High quality analogue 7-channel cassettes were used for the vibration data acquisition phase (Figures 4 and 5).

* See manufacturers' list.

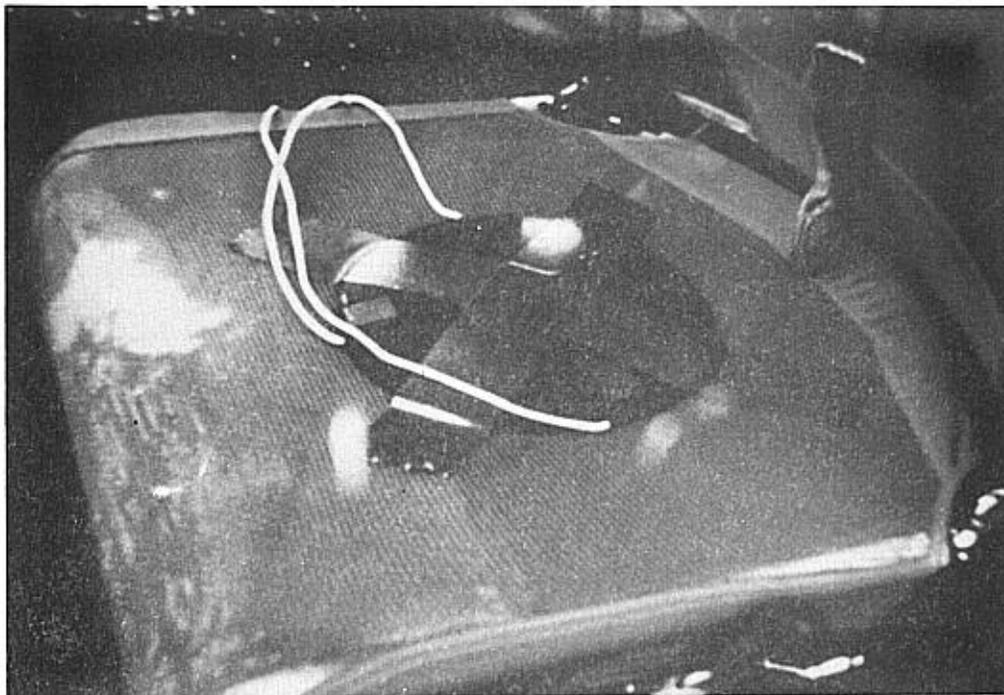


Figure 1. Triaxial accelerometers positioned to transmit vibration signals from seat pad location.

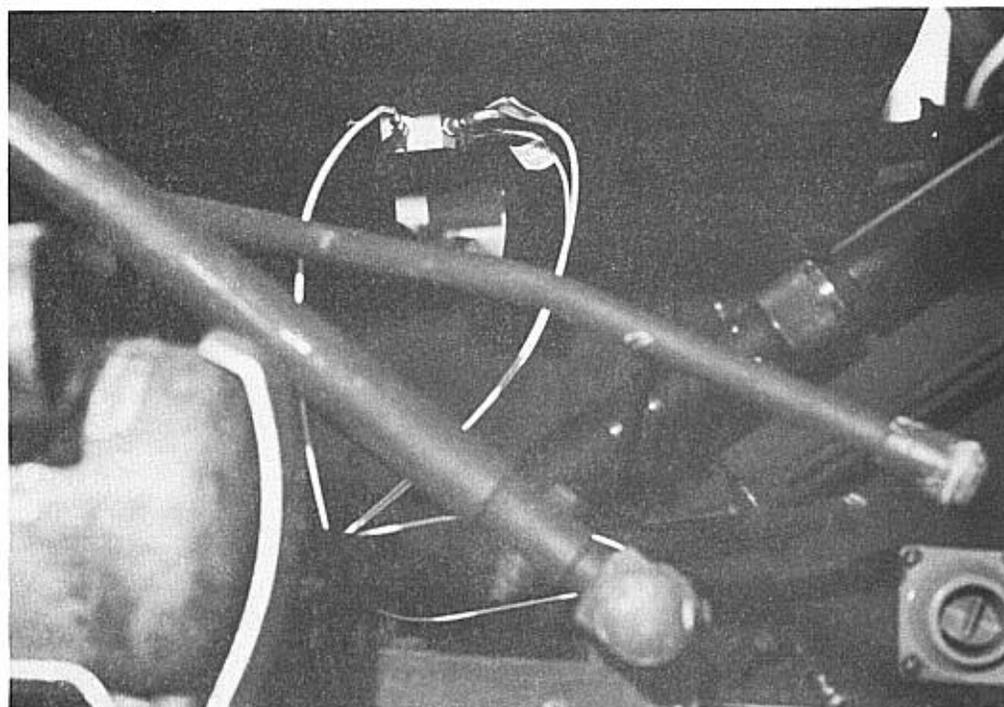


Figure 2. Triaxial accelerometers positioned to transmit vibration signals from seat pan location.

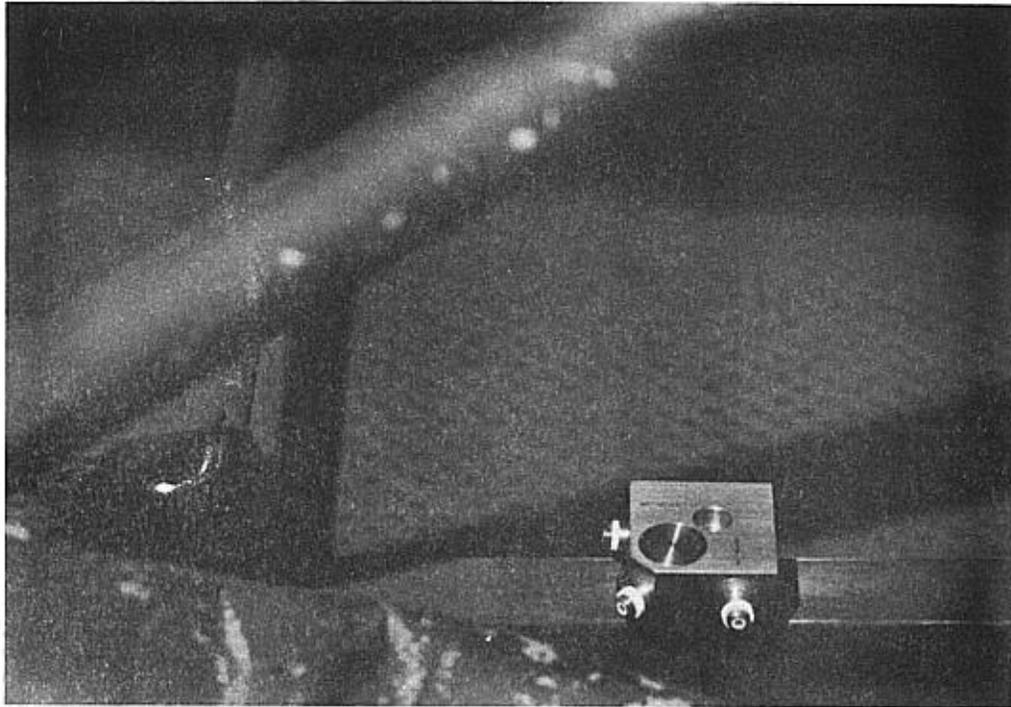


Figure 3. Triaxial accelerometers positioned to transmit vibration signals from floor location.

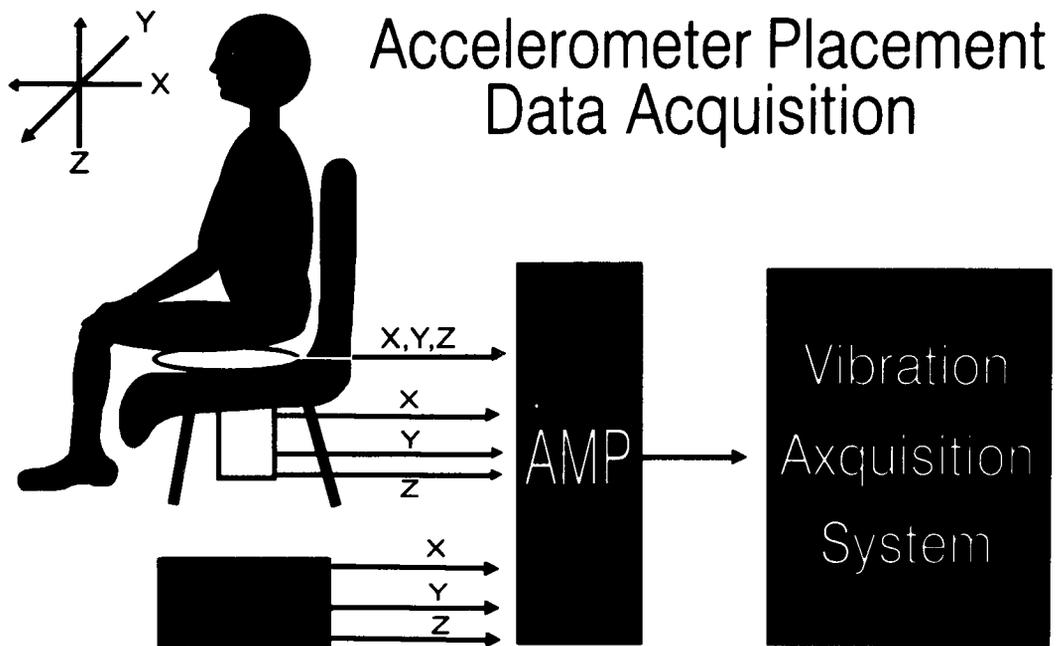


Figure 4. Vibration data acquisition diagram.

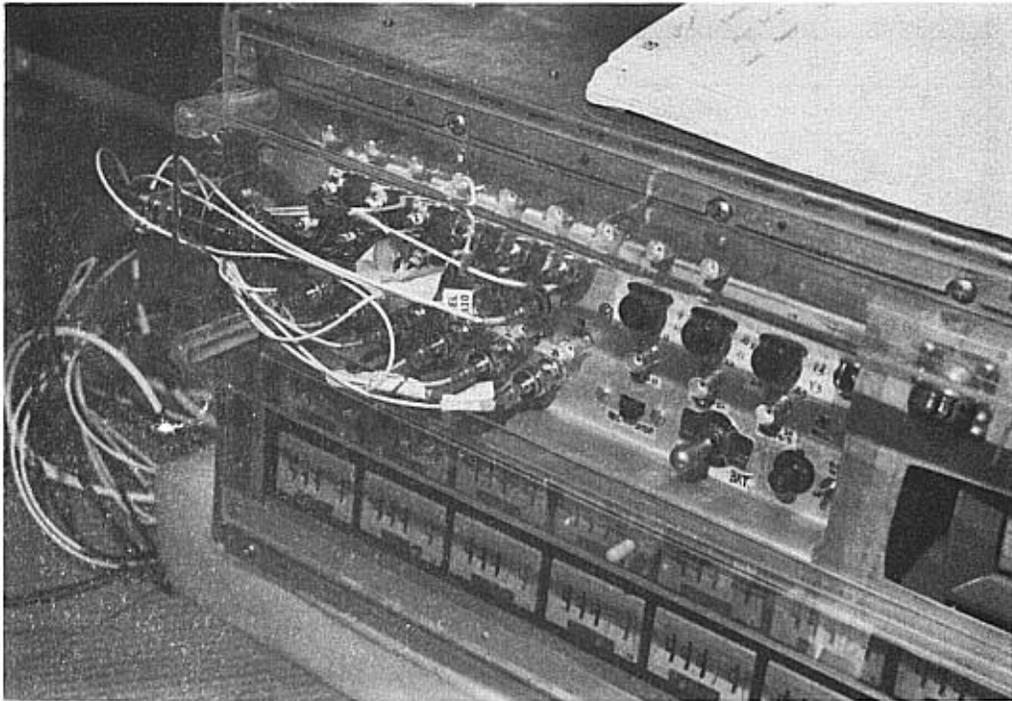


Figure 5. Data acquisition system.

Vibration signatures were taken for both the UH-60 and the UH-1 for a modified version of the flight profile shown in Table 1, provided by ADS-27.

Data analysis

The same recorded WBV signals were played back on a TEAC model MR-30 14-channel recorder/player* into two different signal analyzers. A Larson Davis RTA 1/3 octave analyzer* was used for the ISO 2631 method of vibration analysis, and a Dynamic signal analyzer* was used for the ADS-27 standard method for the analysis of vibration (Figure 6).

Table 1
Test conditions for UH-60 and UH-1

Trial	Manuver	Airspeed	Altitude	Duration
1	Hover IGE	0.00	5 ft	2 min
2	Hover OGE	0.00	50 ft	2 min
3	Hover, pedal, rt	0.00	50 ft	30 sec
4	Hover, pedal, lt	0.00	50 ft	30 sec
5	Forward flt	0.10(Vh)	runway	30 sec
6	Forward flt	0.40(Vh)	runway	30 sec
7	Rearward flt	limit	runway	30 sec
8	Left sideward	0.33 V(lim)	runway	30 sec
9	Right sideward	0.33 V(lim)	runway	30 sec
10	RPM sweep	0.90 Vh .96%	-----	30 sec
11	RPM sweep	0.90 Vh .98%	-----	30 sec
12	RPM sweep	0.90 Vh 1.0%	-----	30 sec
13	Forward flt	0.50 Vh	-----	2 min
14	Forward flt	0.90 Vh	-----	2 min
15	Forward flt	1.00 Vh	-----	2 min
16	Approach flare	rapid 70 kias	-----	-----
17	Approach flare	slow 35 kias	-----	-----
18	Unmask	-----	5-35 ft	-----
19	Mask	-----	35-5 ft	-----
20	Left turn 15/30°	-----	100 ft	2 min
21	Left turn 30/60°	-----	100 ft	2 min
22	Right turn 15/30°	-----	-----	2 min
23	Right turn 30/60°	-----	-----	2 min
24	Climb	-----	-----	-----
25	Descent	-----	-----	-----
26	Vcruise	-----	-----	2 min
27	Vmaximum	-----	-----	2 min
28	Hover IGE	-----	5 ft	2 min
29	Hover OGE	-----	35 ft	2 min
30	Vcruise	-----	-----	2 min
31	Vmaximum	-----	-----	2 min
32	Hover IGE	-----	-----	2 min
33	Hover OGE	-----	-----	2 min

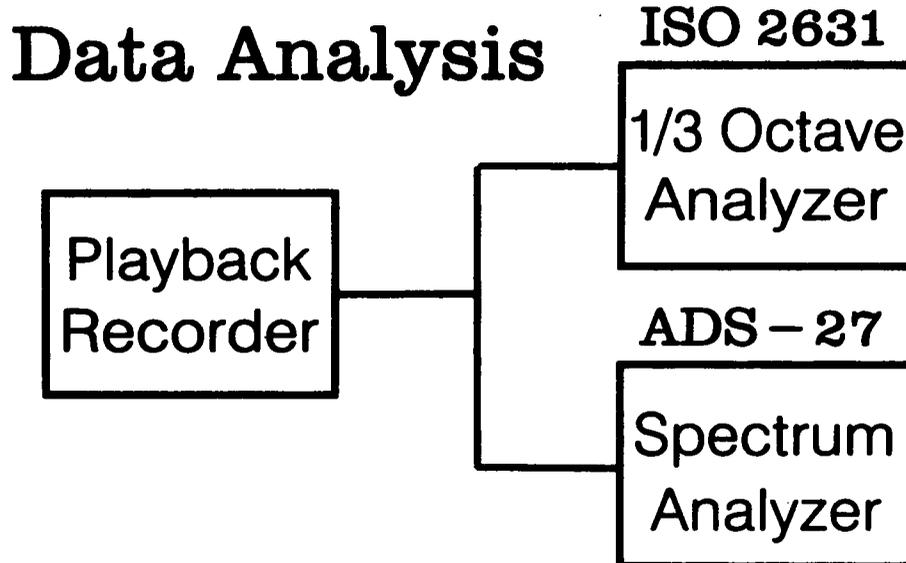


Figure 6. Data analysis diagram.

ISO 2631 method of WBV analysis

WBV translated directly to the pilot, copilot, and crewmembers was measured in terms of root mean square acceleration magnitudes contained in third-octave bands covering a frequency range from 1 to 80 Hz. The Larson Davis 3100 third-octave analyzer* measured the recorded vibration signals and derived magnitudes for all 20 third-octave bands, all flight conditions, and all 3 orthogonal axes of motion. The 8-hour fatigue decreased proficiency (FDP) curve was used as a limit "not to exceed" for the comparison of the two standards. This 8-hour FDP curve is used to determine acceptable vibration levels during the HHA of Army tactical ground vehicles and rotary-wing aircraft. Third-octave levels then were compared to their corresponding ISO 2631 8-hour FDP curve acceleration limits. Conditioned WBV signatures either fell above or below the 8-hour curve FDP limit yielding a respective "unacceptable" or "acceptable" vibration level for that particular flight condition and accelerometer location. All 20 third-octave measurements for all three axes of motion were required to fall under the ISO 2631 8-hour FDP curve limit for that flight condition and accelerometer location to yield an "acceptable" level of WBV.

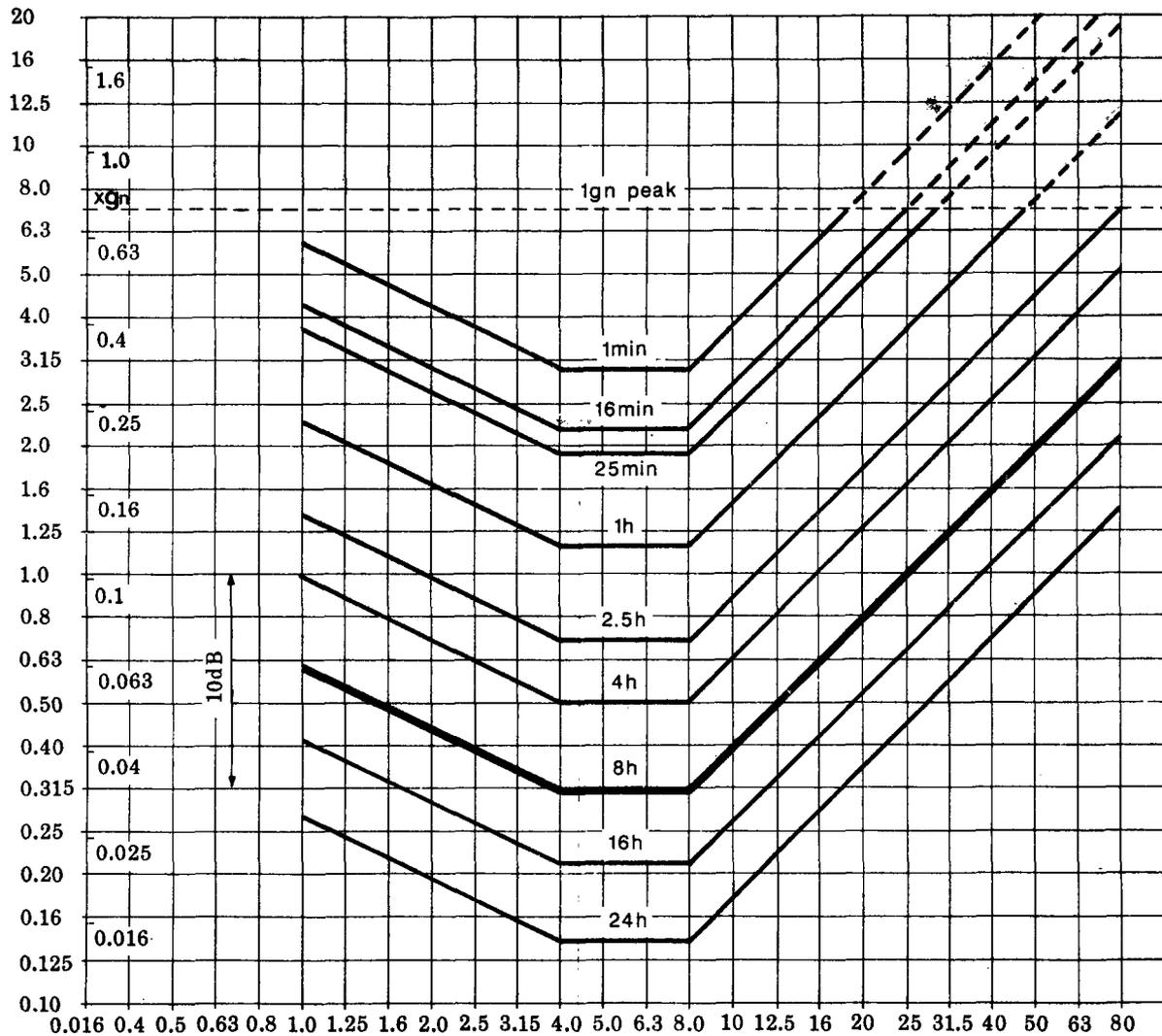


Figure 7. ISO 2631 8-hour FDP curve limit, vertical axis.

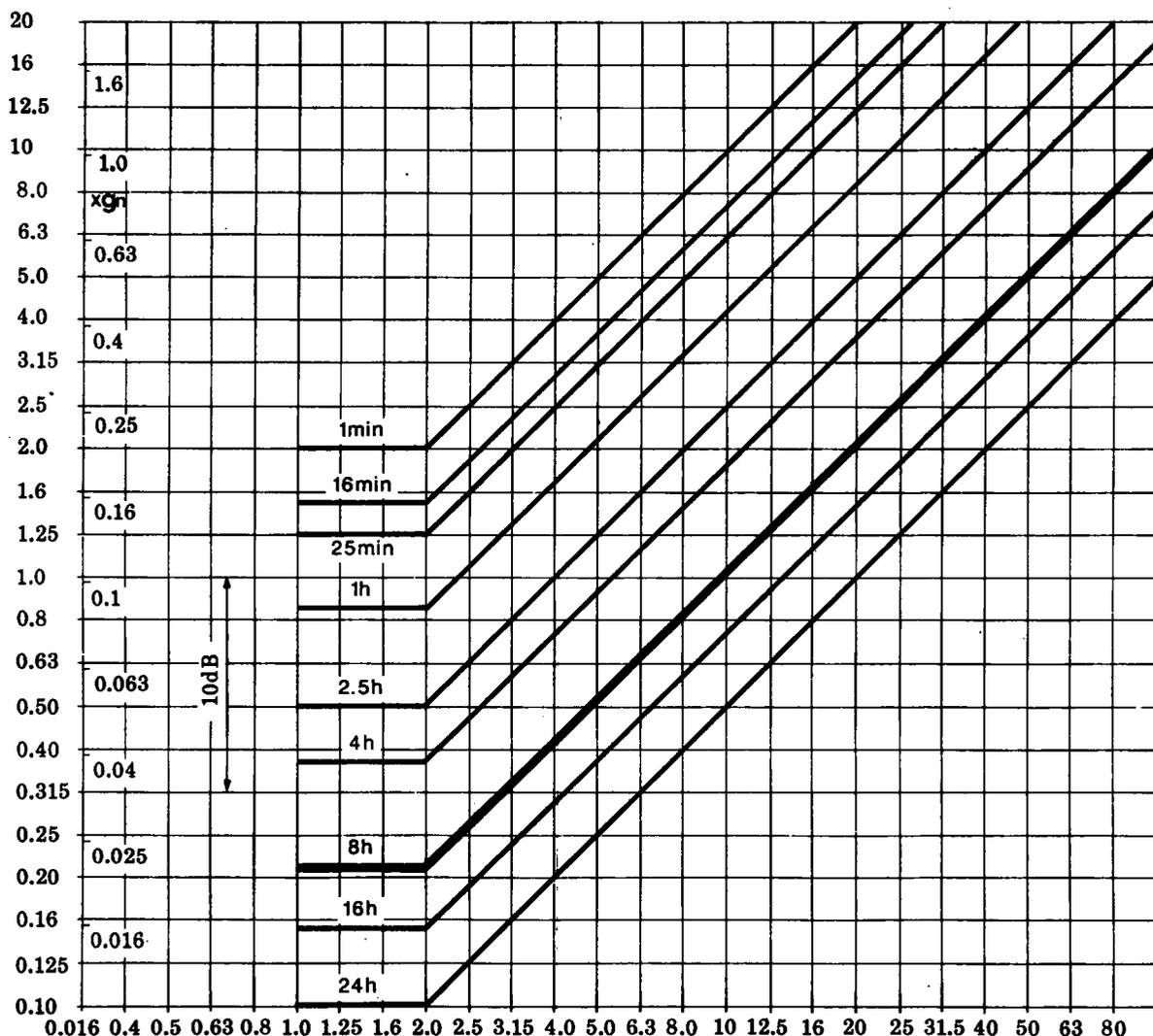


Figure 8. ISO 2631 8-hour FDP curve limit, longitudinal and lateral axes.

ADS-27 method of WBV data analysis

The Hewlett-Packard (HP) 3562 dynamic signal analyzer* is used to obtain a fast fourier transform power spectrum display of WBV signatures for each of the three orthogonal axes of motion, accelerometer position, and flight condition (Figures 9 and 10). A power spectrum displays the discrete sinusoid vibration peaks produced by all types of rotary-wing aircraft. These discrete frequency peaks, lying within the ADS-27 targeted frequency range (0 to 60 Hz), were used to derive a statistical matrix of the WBV produced by each flight condition.

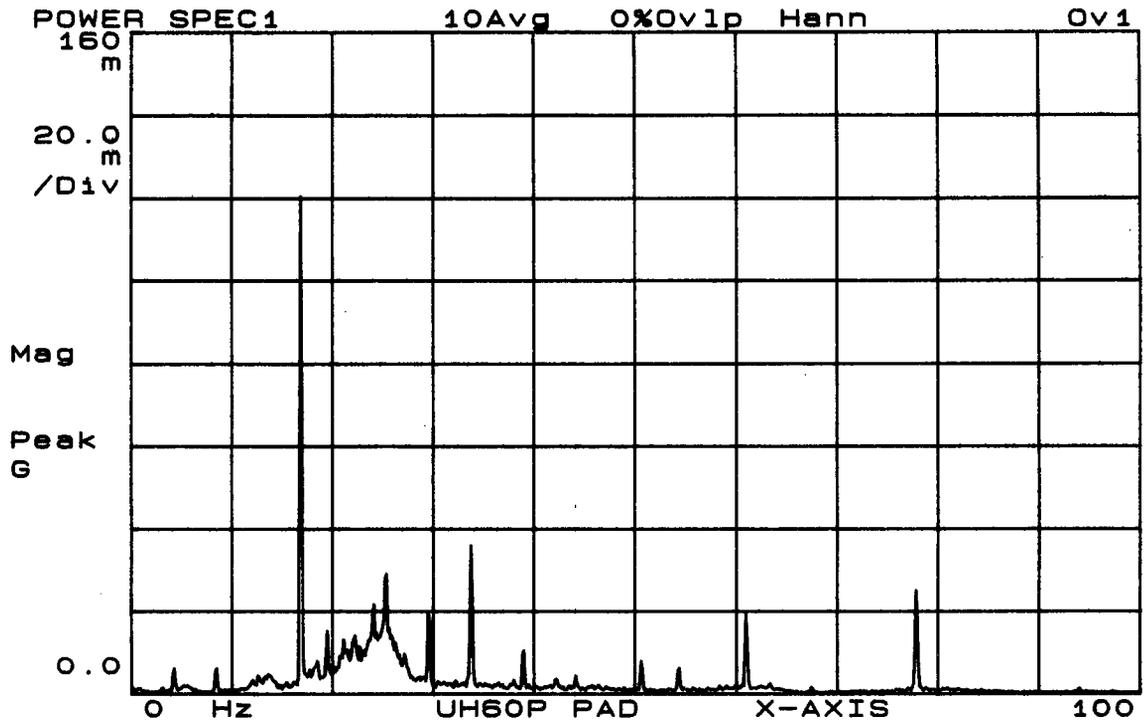


Figure 9a. UH-60 seat pad power spectrum, X-axis.

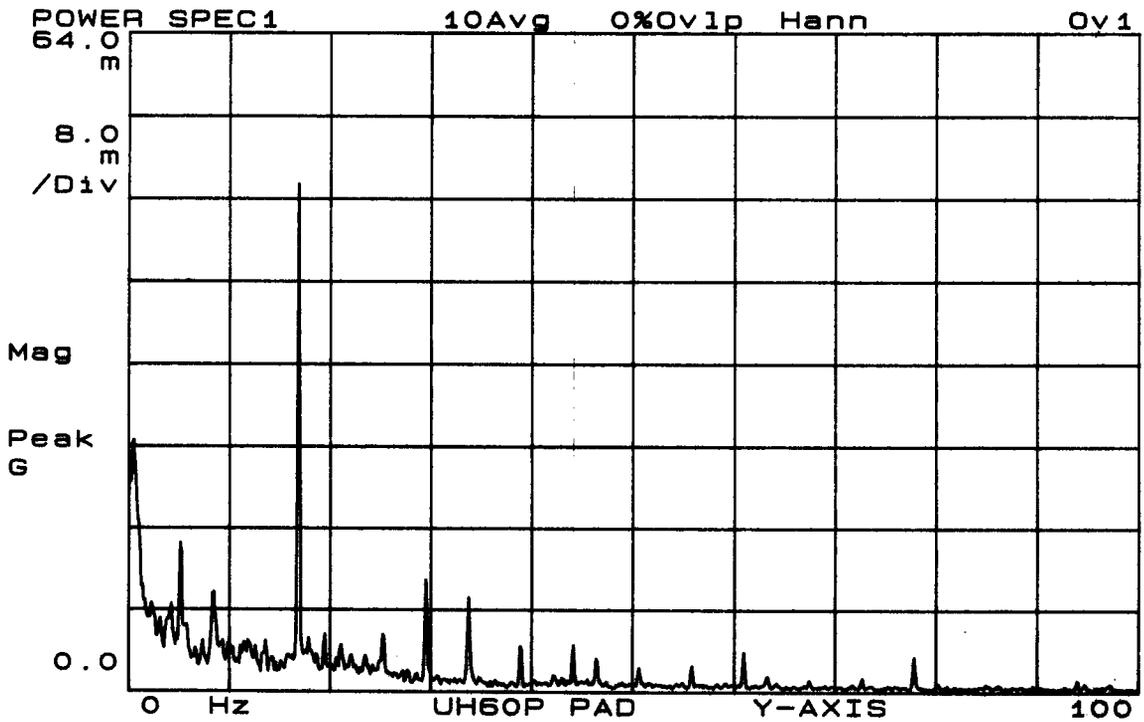


Figure 9b. UH-60 seat pad power spectrum, Y-axis.

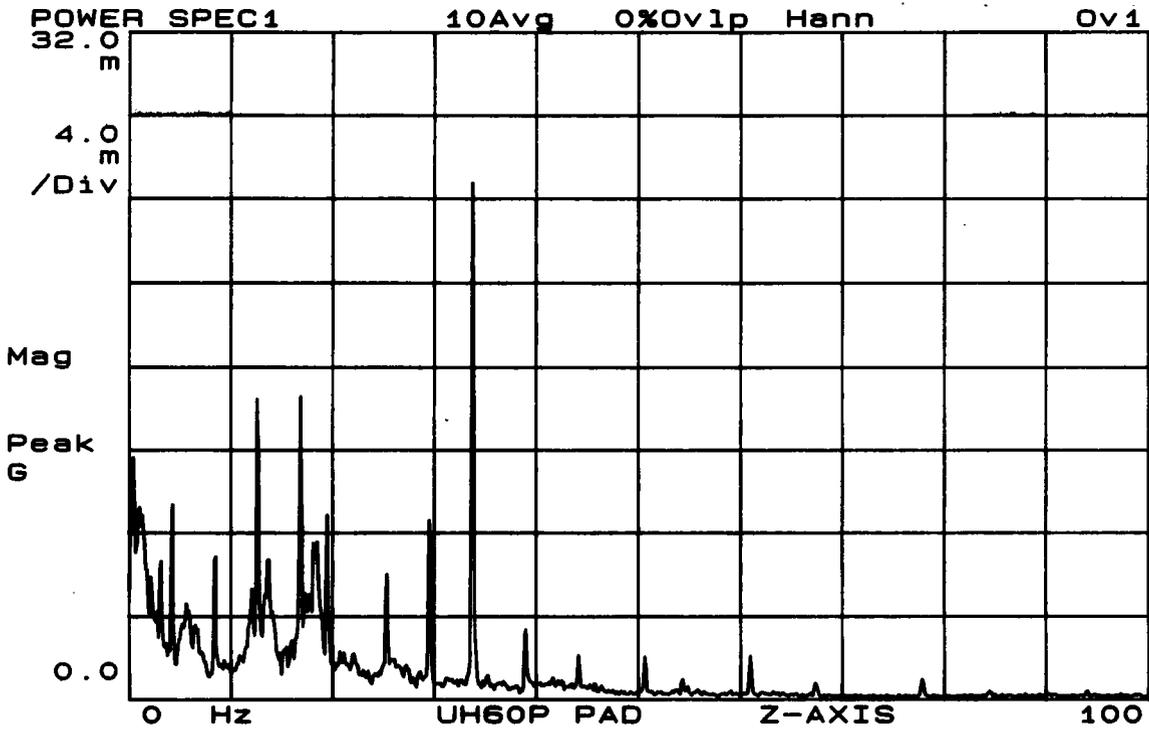


Figure 9c. UH-60 seat pad power spectrum, Z-axis.

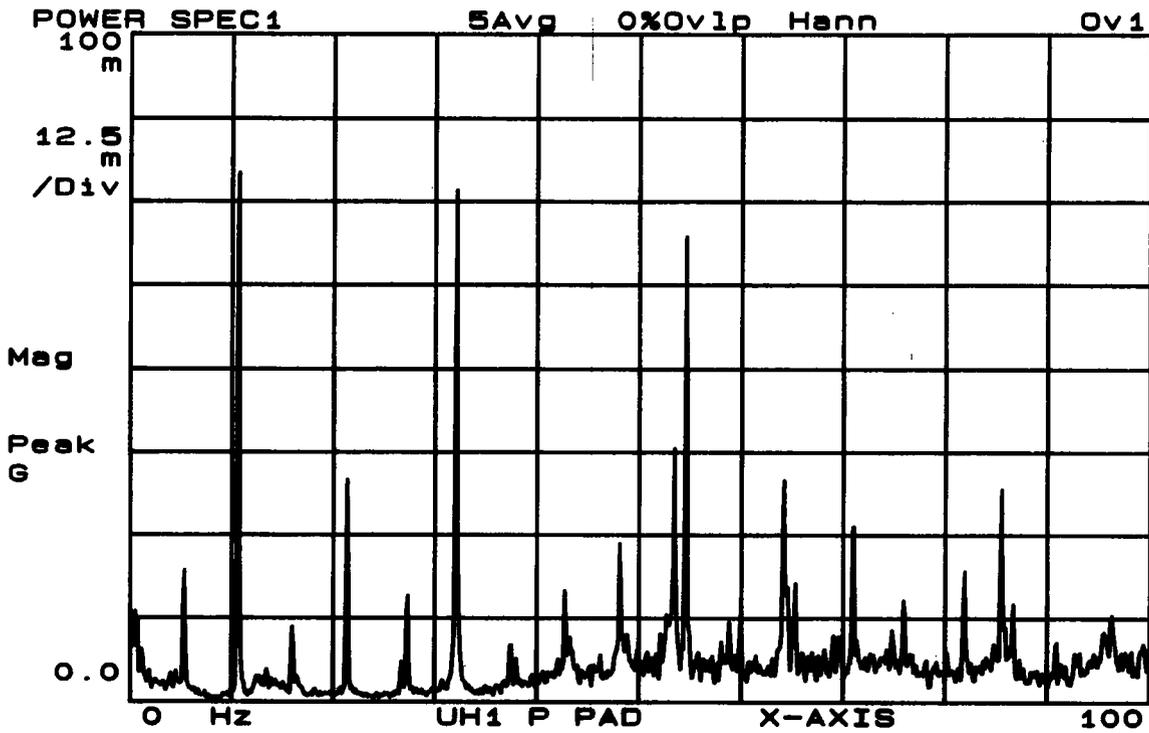


Figure 10a. UH-1 seat pad power spectrum, X-axis.

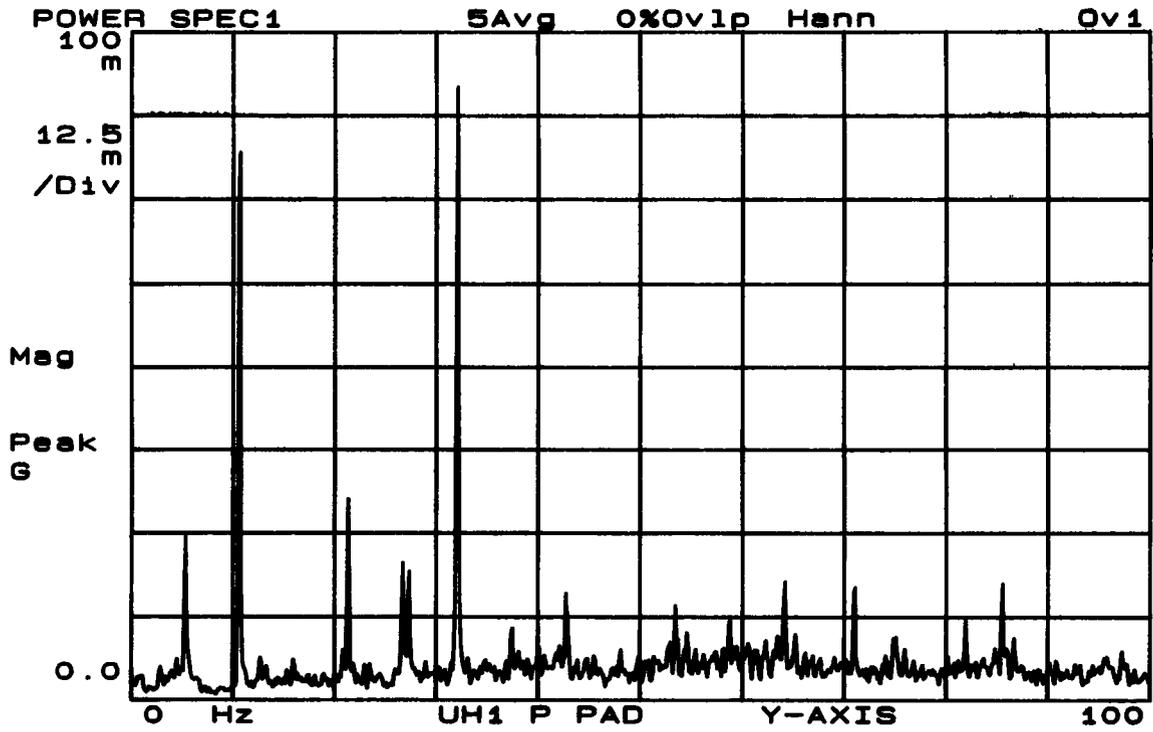


Figure 10b. UH-1 seat pad power spectrum, Y-axis.

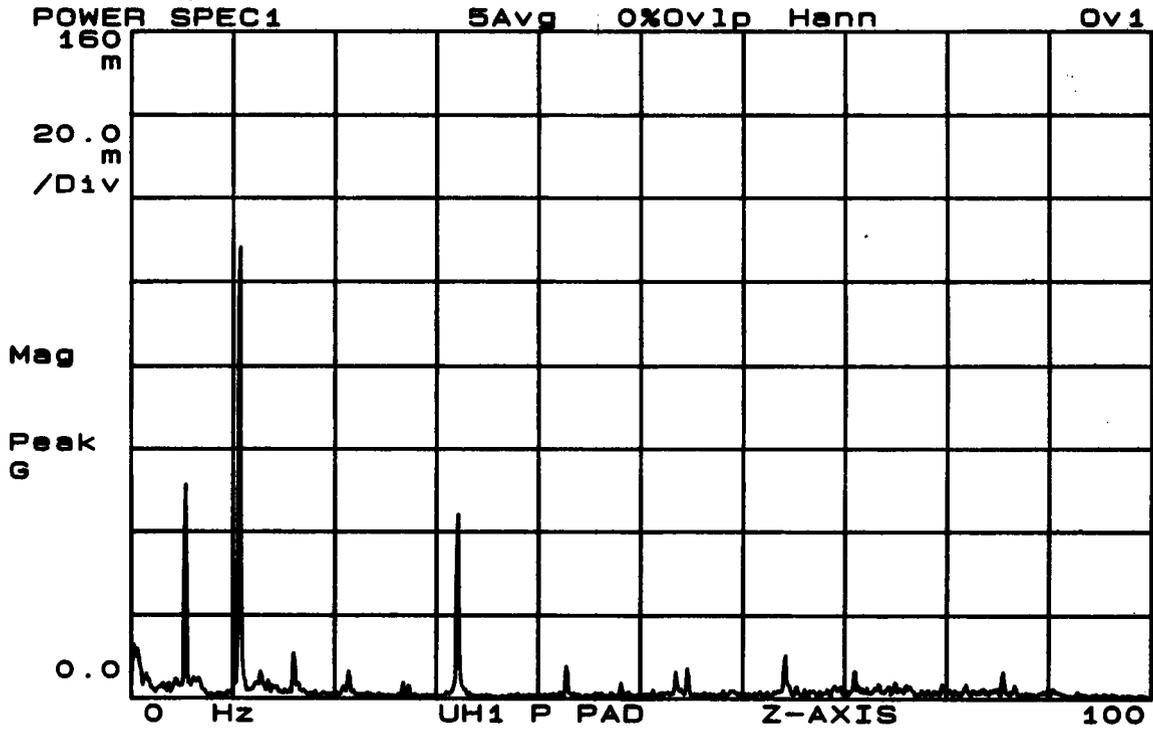


Figure 10c. UH-1 seat pad power spectrum, Z-axis.

This matrix, called an "intrusion index," is calculated by the following process, according to ADS-27: The four largest acceleration peaks, 60 Hz and below, excluding the first blade passing frequency (1BP) (acceleration peak produced by the helicopter's main rotor rpm), for the three normalized vibration spectra shall be identified, converted to a velocity measure, and squared. In Figure 11 can be found the normalization curves used to weigh each power spectrum. The 12 resulting squared values then shall be summed and the square root of that sum calculated (Figure 12). This numeric value is the intrusion index for that particular flight condition and accelerometer location. The intrusion index then is compared to a limit whereby an acceptable or unacceptable rating is derived.

Longitudinal = 0.0 ips at 5 Hz Lateral = .75 x longitudinal
 = 0.46 ips at 40 Hz Vertical = 0.5 x longitudinal
 = 0.54 ips at 60 Hz

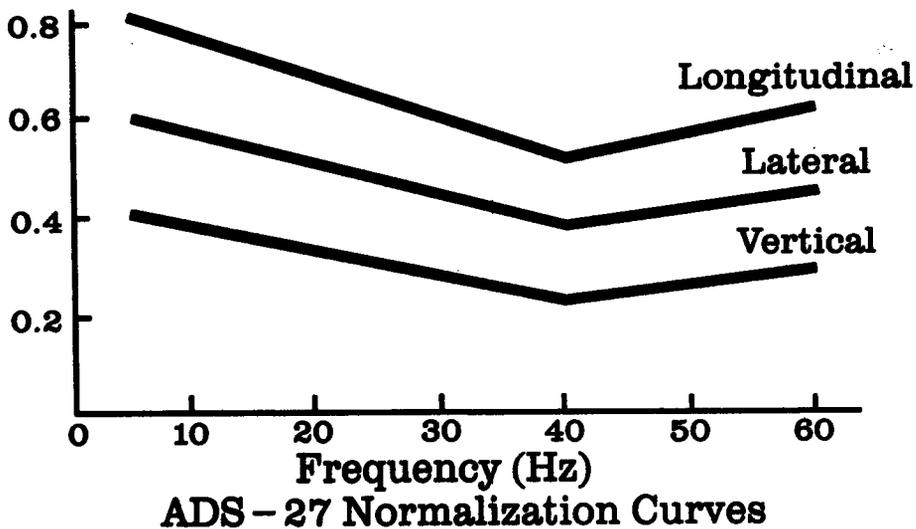


Figure 11. ADS-27 normalization curves.

Intrusion Index

Square Root Sum Of Squares

$$I.I. = \sqrt{\sum_1^4 X_n^2 + \sum_1^4 Y_n^2 + \sum_1^4 Z_n^2}$$

Figure 12. Intrusion index equation.

Under ADS-27, flight conditions fall into four regions. Intrusion index limits are specified for all four regions.

Additionally, ADS-27 uses a limit on the 1BP magnitude for each axis of vibration and flight condition (Table 2). This 1BP limit is used by ADS-27 as a separate criteria. The 1BP limits also vary according to the four flight regions. For instance, if the 1BP magnitude in one of the three axes of motion exceeds the 1BP limit, that flight condition will receive an "unacceptable" WBV rating.

Table 2
Intrusion index and 1BP frequency limits
for flight regions 1 and 2

Pilot

Flight Conditions	Intrusion Index	1BP (IPS)
Region I	1.2	.15
Region II	3.0	.3

Regions 1 and 2 were the only two regions used for this test and will, therefore, be defined here according to ADS-27:

"Region 1 consists of all steady flight conditions with load factors between 0.75 and 1.25 G and airspeeds from hover to normal cruising velocity and to the maximum rearward and sideward flight speeds, while operating within the defined power-on rotor speed limits. Within Region 1 the rotorcraft, aircrew, and all subsystems and equipment must meet the operational performance specifications."

"Region 2 consists of all flight conditions and maneuvers outside of Region 1 which have a duration of greater than 3 seconds. Subsystems and equipment should not incur damage which would result in a lower service life than required during exposure to Region 2 vibrations and must meet their operational performance specifications after exposures of any duration which might be encountered operationally."

Vibration transmission of seating system

To determine the vibration differences between the seat cushion and the seat frame, TEAC MR-30 14-channel recorder/player* and HP 3562A dynamic signal analyzer* were used to obtain a frequency response between seat pan and seat pad accelerometer locations. Frequency responses were used to yield gain and phase differences between input and an output vibrating elements. The input element was the seat pan and the output element was the seat pad. The HP 3562A is configured with channel 1 as the input and channel 2 as the output. Z-axis frequency responses (Figures 13 and 14) were measured during each flight condition for both UH-1 and UH-60 and plotted on a dB versus frequency graph at a frequency range of 1-100 Hz (Figures 9 and 10).

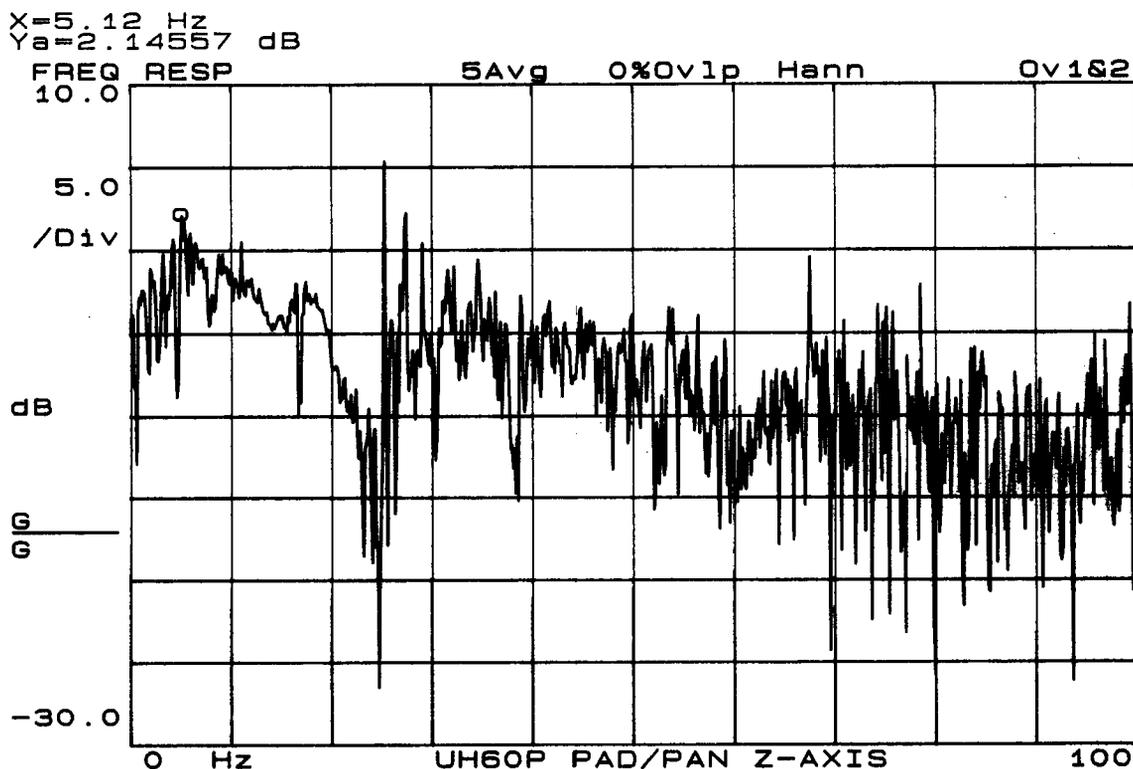


Figure 13. Frequency response graph, UH-60, between pad and pan locations, Z-axis.

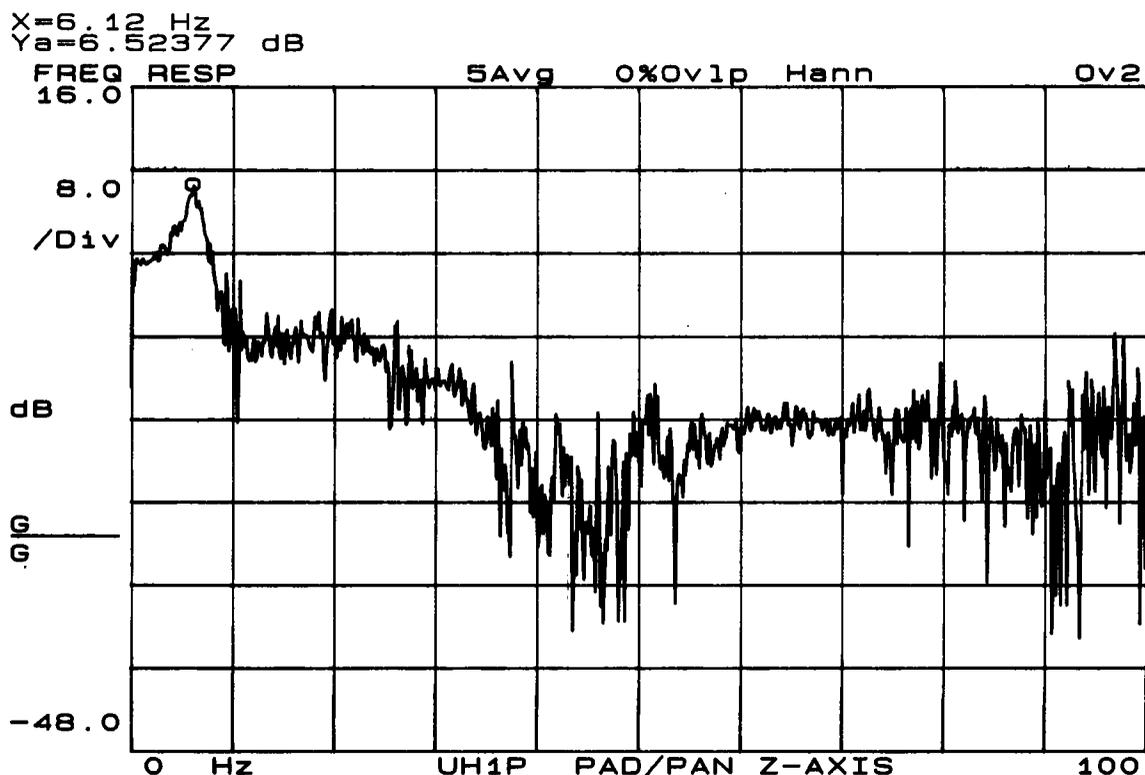


Figure 14. Frequency response graph, UH-1, between pad and pan locations, Z-axis.

Results

Vibration signatures from profiled flight conditions for the UH-1 and UH-60 were analyzed using the ADS-27 and the ISO 2631 WBV standards. Table 3, which presents a percent to pass table of acceptable WBV signatures, was developed for each helicopter type, flight condition, and accelerometer location using both ADS-27 and ISO 2631 methods. Table 3 presents the two ADS-27 criteria: the intrusion index and the 1BP. The first column displays the percentage of acceptable vibration signatures that have been compared with the intrusion index criteria alone and the second column displays the acceptance percentage for vibration signatures that have been assessed using both the intrusion index and 1BP criteria. This combined criteria is denoted as *1BP. Column 3 displays the acceptance rate for the ISO 2631 criteria. The "Total" category denotes the total number percentage of vibration readings taken for that helicopter type. The "Pan" and "Pad" categories denote the total vibration readings taken from the seat pans or seat pads of that aircraft type; similarly, the categories "Co-p" and "P" denote the total vibration readings taken from the pilot or copilot seating systems (seat pad and seat pan locations) for that helicopter type.

Table 3
Percentage of acceptable WBV signatures

	UH-1			UH-60		
	ADS-27		ISO	ADS-27		ISO
	II	1BP		II	1BP	
Total	28%	19.79%	42.71%	61.50%	30.68%	59.10%
Pan	24%	20.83%	31.25%	57.69%	29.54%	50.00%
Pad	32%	18.75%	54.16%	65.38%	31.80%	68.20%
Co-P	12%	10.40%	8.30%	67.30%	29.50%	75.00%
P	44%	29.16%	77.08%	55.76%	31.80%	43.18%

Table 4 displays the average intrusion index for the UH-1 and UH-60 at all accelerometer positions.

Table 4
Average intrusion index

Aircraft	Accelerometer location	Pilot/copilot	Average intrusion index
UH-60	Pad	CP	1.5200
UH-60	Pan	CP	1.7440
UH-60	Pad	P	1.4132
UH-60	Pan	P	1.7900
UH-1	Pad	CP	2.434
UH-1	Pan	CP	2.995
UH-1	Pad	P	1.629
UH-1	Pan	P	1.932

Discussion

When studying the results of Table 3, consideration must be placed on the accelerometer location specified by each of the two standards. As previously mentioned, ADS-27 calls for the accelerometer to be located at the "seat pan," while ISO 2631 defines the "seat pad" as the proper accelerometer location for capturing WBV signatures. The vibrations that have been measured from the two specified locations will be of primary interest, especially when comparing the two standards.

Evaluation of the UH-60 WBV data

Based on the intrusion index and using specified "seat pan" accelerometer location, 57 percent of the signatures were judged as acceptable. The acceptability rate was reduced to 29 percent when the intrusion index and the 1BP criteria were combined to form the *1BP category. On the other hand, the acceptance rate of 68 percent was obtained when UH-60 "seat pad" vibration data was analyzed according to ISO 2631.

Evaluation of the UH-1 WBV data

Using the intrusion index alone as a criterion yielded a 24 percent passing rate. When the intrusion index and the 1BP criterion was used to assess the whole-body signatures, only 20 percent of the signatures were found acceptable. The ISO 2631 acceptance rate was 54 percent.

From this comparison alone, ADS-27 was seen to be the more stringent standard. Also, it is evident the combined criteria, *1BP, make ADS-27 the significantly more stringent WBV vibration standard.

Table 4 indicates the "average" intrusion index for the UH-60 and the UH-1 at the different accelerometer locations. Two conclusions can be drawn from this table: First, the UH-1 vibrates with a greater force than the UH-60 and second, when seat pad and seat pan accelerometer vibration data were analyzed according to intrusion index criterion, seat pan accelerometer output consistently yielded a greater average intrusion index.

The 1BP portion of the ADS-27 fix WBV acceptability levels for the 1BP passing frequency magnitudes in all three orthogonal directions (X-, Y-, Z-axes). 1BP frequency magnitudes are proportional to the mechanical vibration induced by a helicopter's main rotor during normal rotation. Variations of 1BP magnitude variations that occur among similar aircraft may be due to differences in systems tracking and levels of mainte-

nance. 1BP magnitude variations that occur in the same aircraft may be generated by the differences in flight regimen and a variety of pilot flight styles. Since the 1BP is an unstable measure of vibration in similar aircraft, and no correlation has been determined between 1BP magnitudes and intrusion index levels for nearly identical flight conditions, 1BP measures should not be used as a guide for indicating the vibration levels in specific type helicopters. 1BP measures serve to diagnose problems in rotor blade tracking and may indicate flight conditions with pronounced vibration magnitudes produced by the 1BP frequency. 1BP vibration magnitude peaks are found in that frequency range most sensitive for humans and, therefore, must not be ignored.

The ADS-27 standard specifies the seat pan as the primary location for accelerometer placement. The seat pan should not be considered a direct input of vibration to the pilot or copilot, for to do so would be to ignore the damping and amplifying effects of the seat cushion. The seat pan is the prefiltered vibration that was transferred from the helicopter frame through the seat legs to the hard under-portion of the helicopter seat. Frequency transfer functions between the seat pan and the seat pad accelerometers indicate that helicopter frame vibration is amplified and/or attenuated over the frequency range of concern (1-80 Hz). Frequency responses between the seat pan and the seat pad should be a major consideration when analyzing input of vibration levels to a pilot.

The ADS-27 is primarily a rotary-wing aircraft design standard used for the purpose of issuing Requests for Proposal (RFP) and subsequent procurement specifications. The standard was modified to measure frame vibration in specific locations within the helicopter, specifically, vibration near pilot and crewmember locations. ADS-27 offers a method to quantify helicopter WBV and may be used to identify areas within the aircraft that introduce the greatest vibration magnitudes. ADS-27 derives its WBV numeric value (i.e., the intrusion index) from limitations on helicopter pilot and crewmember performance while it bypasses the health-related aspects of WBV.

The ISO 2631 recognizes the various elements (performance, comfort, fatigue, and health) as the essential ingredients in developing WBV assessment criteria. This standard has been criticized for the weak basis for the development of its health hazard criteria. At the time of ISO 2631's development, research data suggested in order for a human to "endure" longer exposures to vibrations without injury their levels must decrease. Furthermore, since the data was limited, extrapolations to longer durations were made using mathematical modeling and some fundamental assertions. However, most critics of ISO 2631 avoid the health element in their assessment of WBV.

Although data on vibration-induced injury may be scarce, inconclusive, and may be a weak basis for setting exposure limits for the purpose of making HHAs, the relationship between injury and WBV has been shown to exist and should be accounted for.

Conclusions

Both the ISO 2631 and ADS-27 have deficiencies which are difficult but not impossible to overcome. ADS-27 is a statistical measure of mechanically-induced rotary-wing aircraft vibration. The method is based on the levels of vibration from the aircraft frame and yields a number value for this vibration. The ISO also uses vibration from the aircraft, but takes its level measurement from the man-machine interface location (i.e., the seat pad). The ADS-27 is derived primarily from pilot performance data and may be considered as a misplaced aircraft design standard which was modified to emulate a WBV standard much like the ISO 2631. When vibration levels are measured on a pass/fail criteria, the ADS-27 standard becomes the more stringent standard. But, ADS-27 fails to answer the important health hazard questions that ISO 2631 attempts. Until a more definitive and militarily-relevant WBV standard is developed, the use of both ISO 2631 and ADS-27 may be a more complete method of helicopter WBV analysis.

References

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- Kidd, David L. 1981. Assessment of helicopter vibration criteria. Fort Worth, TX. Bell Helicopter Textron. Presented at the American Helicopter Society 37th Annual Forum. New Orleans, LA.
- Osborne, D. J. 1983. Whole-Body Vibration and International Standard ISO 2631: A Critique. In: Human Factors. 25(1), 55-69.

Appendix

List of equipment manufacturers

Bruel & Kjaer Instruments, Inc.
Forest Street
Marlborough, MA 01752

Hewlett-Packard Company
4700 Bayou Blvd, Suite 5
Pensacola, FL 32505

Kistler-Morse
10201 Willows Road, N.E.
Redmond, WA 98073

Larson Davis Laboratories
280 S. Main Street
Pleasant Grove, UT 84062

Lee Associates
815 Wheeler Avenue
Huntsville, AL 35801