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Vibration Environmental Testing for Large Haulage Trucks

By John C. Gagliardi and Walter K. Utt

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

U.S. Department of the Interior
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

g^2/Hz	square g (acceleration) per hertz
h	hour
Hz	hertz
MHz	megahertz
min	minute
m/s^2	meter per square second
mV/(m/s^2)	millivolt per meter per square second
pct	percent
s	second
st	short ton
V	volt

VIBRATION ENVIRONMENTAL TESTING FOR LARGE HAULAGE TRUCKS

By John C. Gagliardi[1] and Walter K. Utt[2]

ABSTRACT

The size and complexity of modern surface haulage trucks has resulted in an increased reliance upon sensors and electronic-based instrumentation for safe and efficient operation. Design engineers need accurate information about the equipment vibration environment to efficiently and effectively build components for installation on mobile mining equipment capable of withstanding the mine environment. Examples of such components include backup alarms, communication equipment, microprocessor-based controllers, and a wide variety of sensors. Unfortunately, this information is not available to the majority of both original equipment and aftermarket equipment manufacturers. To address this problem, the U.S. Bureau of Mines performed field vibration measurements on a variety of surface mining haulage trucks. The vibration measurements were then analyzed and test specifications were developed in the form of envelopes. In conjunction with test specifications, recommendations to aid manufacturers in implementing a vibration environment test program have been included with an illustrative example.

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INTRODUCTION

Surface mining equipment is becoming much more sophisticated and complex. Machinery controls and self-diagnostics are increasingly relying on sensors and electronic microprocessor-based systems. Controls in surface haulage equipment are now employing technology previously only found on advanced aircraft, such as joysticks to control vehicle direction and speed. Sensors to monitor equipment operating conditions, such as hydraulic fluid level, engine temperature, and engine pressure, are tied into electronic modules. The safe operation of these machines is increasingly dependent on the reliable functioning of control, diagnostics, warning, and communication electronics.

Field testing is a common method to qualify electronic equipment to survive work environments containing severe vibration levels. Field testing will uncover design flaws. Most times, however, improper design may only reveal itself after many hours of application, making field testing a very slow process (*1*).[3] With the fiercely competitive international business world of today, the implementation of state-of-the-art technology is necessary for all phases of the design process. Hence, field testing is an inefficient process. If product qualification is not performed, the product may be underdesigned or overdesigned. Underdesigned products are unreliable, while overdesigned products are expensive (*2*). An underdesigned, unreliable product leads to customer dissatisfaction and prohibitive warranty and repair work. An overdesigned product leads to wasted material and increased production costs.

The military realized the essential need of reliable products to ensure mission success and made environmental testing a necessary requirement for all military equipment. Military standard (MIL STD) 810 (MIL-STD-810E, most recent version), entitled "Environmental Test Methods and Engineering Guidelines" (*3*), was created to provide methods for testing equipment to survive their natural and induced environments and to determine the effect that the environment had on the equipment. MIL-STD-810E provides test methods for natural and induced environments concerning temperature, humidity, dust, vibration, etc.

Application of environmental testing to the commercial sector of industry has become a standard part of operation for some companies but has been relatively ignored by others. One reason for the slow acceptance of environmental testing for commercial products is the uncertainty of an economic payoff. Other factors that may influence management's decision not to test are a lack of instrumentation to make baseline environmental measurements, facilities to conduct laboratory testing, and expertise to perform the test.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

The following obstacles for incorporating a qualification program in the design process have been cited (*4*):

1. Significant expense.
2. Limited field measurement and analysis capabilities.
3. Time-consuming analysis, requiring human resources.
4. Payback justification.

The two major types of product vibration tests conducted are environmental stress screening and qualification testing. Environmental stress screening is used to uncover construction flaws or deficiencies in the manufacturing process. Qualification testing is composed of two parts, functional and endurance testing. Functional testing is used to verify that the product will not suffer any performance degradation when subjected to the work environment. Endurance testing is used to accelerate the fatigue in a product to an equivalent cumulative amount representative of the amount that would be acquired over the product's entire operating life. This report will exclusively cover qualification testing of electronic equipment.

Electronic equipment that performs intermittently or causes unexpected failure could significantly raise safety risks. Common failures in electrical equipment caused by vibration cited in MIL-STD-810E (*3*) and SAE J1211 (*5*) are identified as—

1. Wire chafing.
2. Loosening of fasteners.
3. Intermittent electrical contacts.
4. Touching and shorting of electrical parts.
5. Seal deformation.
6. Component fatigue.
7. Optical misalignment.
8. Cracking and rupturing.
9. Loosening of particles or parts that may become lodged in circuits or mechanism.
10. Excessive electrical noise.

As part of its program to increase safety for the mine worker, the U.S. Bureau of Mines (USBM) conducted tests on mining machinery to reduce the possibility of electronic equipment operating improperly. Field measurements were obtained on operating large haulage trucks to quantify their vibration environment. These measurements were analyzed, and from the results, vibration test specifications in the form of envelopes were developed. An envelope was constructed to equal and/or exceed vibration levels typically encountered in the field. The development of a qualification test program is presented (*3-4, 6*) with an illustrative example to aid manufacturers not currently implementing vibration qualifications

TRUCK DESCRIPTION

Haulage trucks are tailored for the mining industry's requirements (7). Trucks typically have capacities ranging from 85 to 240 st. The two basic truck designs are rear dump and bottom dump. Rear-dump trucks are typically used for applications such as overburden removal or transportation of material that consists of large fragments. Because of the bed being one unit, rear dumps can allow high impacts when loading. In addition, rear dumps do not require the material to be free flowing or require any special facilities for dumping. The typical design of a rear-dump truck consists of a rigid frame, front and rear axle, rear drive, and dual rear wheels. Bottom dumps typically haul high-grade material to processing facilities containing dumping stations. Because the bed floor of the bottom-dump truck swings open, the material hauled must be free flowing and fairly light in density. Bottom-dump trucks are commonly used to haul coal. Bottom-dump trucks are rigid two-axle type or tractor-trailer, three-axle type. Because of the large number of rear-dump trucks typically used in mining applications, vibrational field measurements were obtained exclusively on rear-dump haulage trucks.

Haulage trucks are filled by front-end loaders, electric shovels, or hydraulic excavators. Depending on the type of material loaded, the truck will proceed either to a spoil area to dump overburden or to a material processing unit, such as a crusher for ore or coal haulage. Truck speed may vary during different parts of the haul cycle. Various axle-frame-suspension design types for haulage trucks are compressible fluid cylinders, rubber-column struts, and hydropneumatic cylinders.

The drives on haulage trucks can be either mechanical or electrical. Mechanical drives consist of automatic power shift transmissions and torque converters for decreased driveline shocks and high starting rimpull torque. Designs to increase torque include nonslip differential and final planetary gear reduction in the wheel hubs. Hydraulic retarding is provided to reduce braking load.

Haulage trucks with capacities greater than 85 st may employ electric drive trains. Electric drive trains consist of an alternator, rectifier, dc motors, and retarders. The drive wheels contain dc motors. During retarding operations, the dc motors act as electric generators, dissipating the power as heat to a resistive grid.

The results presented in this report are from six trucks. The truck manufacturers were Wabco[4] (currently owned by Dresser Industries Inc.), Unit Rig, and Euclid (currently owed by VME). The truck capacities are 85, 120, and 170 st.

FIELD MEASUREMENTS

From 1984 through 1990, USBM researchers traveled to various surface mines located throughout the United States to obtain vibration measurements on haulage trucks and various other mobile surface mining machinery to provide vibration environmental test envelopes. The surface mines visited produce copper, coal, gold, silver, aggregate, sand, lithium, and various other commodities.

In addition to large haulage truck measurements, various other types of surface mining machinery, such as hydraulic shovels, blasting drills, scrapers, front-end loaders, graders, track dozers, rubber tire dozers, and under 85-st-capacity trucks were measured. Mining machines were instrumented with vibration sensors mounted at various locations. The instrumented machinery performed its typical work operations while vibration measurements were being obtained simultaneously. Field vibration measurements will provide information for accurate test spectrum level and shape. Field measurements are necessary because presently no general analytical environmental modeling method exists for test applications (3).

MEASUREMENT LOCATIONS

Vibration measurements were obtained on major components at various locations on the haulage trucks. Major sites of measurement locations presented in this report were the alternator, cab, engine, frame, hydraulic pump, and wheel. The wheel acceleration's input source was primarily terrain-vehicle interaction and was measured before the primary vertical suspension. The frame was the truck's superstructure that supports the bed, cab, and engine and was supported by the primary suspension. The cab was defined as being the operator's vehicle control compartment. The other locations (alternator, hydraulic pump, and engine) were specific components. Vibration measurements were obtained triaxially in orthogonal orientations for the above locations. The triaxial orientations were defined as x (longitudinal or fore-aft), y (lateral or side to side), and z (vertical or up and down). The results were constructed with all measurement orientations combined together. The triaxial measurements were combined to increase the confidence that the true vibration environment was being represented in the constructed test envelopes from field measurements. The vibration test envelopes were obtained on large haulage trucks and hence are recommended for electronic equipment mounted on haulage trucks.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

INSTRUMENTATION

Vibration sensors employed were internal preamplifier piezoelectric accelerometers. The accelerometers were from various manufacturers and had varying sensitivities. Typically, locations where high-amplitude accelerations were expected used low-sensitivity accelerometers [1 mV/(m/s^2)] and low-amplitude accelerations used high-sensitivity accelerometers [10 mV/(m/s^2)]. The power supply for the accelerometers were battery-powered Vibrometer P-16's. The accelerometers were stud mounted to aluminum blocks in the triaxial orientations described above. The aluminum blocks were then glued to the truck using cyanoacrylate and epoxy. The cyanoacrylate was used for a quick set while the epoxy was placed along the edges for shear strength. The outputs from the accelerometers' power supplies were connected to a telemetry transmitter's input.

TELEMETRY SYSTEM

A radio telemetry system was used to allow the instrumented vehicle to perform regular work without any restrictions while, at the same time, not exposing delicate recording equipment to the harsh surface mine environment. The radio telemetry system has two major components, a transmitter and receiver. The telemetry system was an FM-FM design. Each measurement channel has its own subcarrier frequency, which was assigned by a voltage-controlled oscillator (VCO). The VCO outputs were mixed together and FM modulated on a 216.5-MHz carrier frequency. The transmitter mounted on the vehicle was powered by a 12-V deep-cycle marine battery. The output signal was sent via a transmitting antenna. The transmitted signal was detected by a receiver. The signal's carrier frequency was stripped off by the receiver. The signal was then simultaneously passed through 14 demodulators corresponding to the subcarrier frequencies of the VCO modules. The demodulated signal of each channel was then recorded on a 14-channel data recorder. The receiver and recorder were powered within an instrumentation van equipped with gas-powered electric generators.

MEASUREMENT RECORDING

While the haulage trucks performed their regular work cycle, video information and vibration measurements were recorded simultaneously. The video recordings were obtained using a VHS camera. Video recordings of the work operation were obtained to help correlate vibration measurements with work operations. The vibration measurements were recorded on a 14-channel data recorder, as previously mentioned. The recorded vibration measurements were subsequently analyzed at the USBM's Twin Cities Research Center's shock and vibration laboratory.

After the vibration field measurements of the operating trucks and video recording of the entire work cycle were conducted, the first step in deriving a qualification test specification was completed. The qualification test is specified by test time, vibration level, and direction of excitation. The next step to derive a test specification was the determination of the stresses that the equipment experienced throughout its worklife history (*4*). The average time for the filling, moving-loaded, dumping, moving-empty cycle was around 10 min for a typical mining operation. The estimated average operating lifetime of a haulage truck was 40,000 work hours. Hence, a normal haulage truck will perform 240,000 work cycles in a lifetime. The truck vibration levels were analyzed for the moving-empty and moving-loaded portions of the work cycle, and these results were included in the construction ofthe vibration test envelopes. The stress history of the equipment from the moving-empty and moving-loaded portions of the haul cycle contributed to the derivation of the test specification. Although the shocks experienced by the truck due to filling and dumping may effect the equipment's useful worklife, these effects were not included in the vibration envelope construction. Laboratory shock testing of equipment parts would better simulate the dumping and filling effects.

ANALYSIS PROCEDURE AND EQUIPMENT

The recorded vibration signals were played back into a GENRAD 2514 vibration control system. The GENRAD 2514 is a computer-based, software-controlled, closed-loop vibration testing system; the GENRAD 2514 system also has digital signal processing (DSP) capability. The GENRAD 2514 is a DEC LSI-11 microcomputer interfaced with analog-to-digital and digital-to-analog subsystems. The software utilized for analysis on the GENRAD 2514 system was the Interactive Signal Analysis Program (ISAP). ISAP is a multichannel spectral analysis software package, which uses digital fast Fourier transform and other processing techniques to perform analysis of analog input signals. The DSP performed was power spectral density (PSD). The PSD is defined as the intensity of random vibration in terms of mean-squared acceleration per unit of frequency (g squared per hertz). The units of acceleration are g's (9.8 m/s^2) and the unit of frequency is the hertz. In general, the vibration spectrum of wheeled vehicles and trailers is predominantly random, with peaks and notches considerably higher and lower than the mean level at various discrete frequency bands (*3*).

Before analysis, tests were conducted to determine the affects that window shape had on spectrum leakage. A window is a weighting applied to the time series vibration samples. The value of the weight is dependent on when a particular vibration sample was obtained. It was found that for pure tones, leakage was minimal when no window was applied. Because windowing (1) alters the time series, (2) requires a correction factor to produce overall values equal to actual levels, and (3) contains spectral leakage, analysis results were obtained using no window.

The bandwidth of the vibration signal analysis was limited to the bandwidth of the telemetry system. The telemetry bandwidth was 2,000 Hz. Analysis was performed over a bandwidth of 2,000 Hz and a resolution of 800 lines. The resulting frequency resolution was 2.5 Hz.

Frame vibration is nearly true random vibration for many locations and was analyzed using random signal analysis techniques (*1*). By analyzing the data using random analysis, random analysis results are compatible with random vibration tests. Engine vibration contains periodic signals because of the engine firing. The vibration levels experienced were dependent on engine load and speed. For the engine, random vibration analysis should be performed with field measurements and shaker tests using the same analysis frequency resolution bandwidth (*1*). The excitation at periodic frequencies of a particular engine may be greater than given in this report. The lower levels in this report are due to averaging results from many different engines. For a particular frequency of interest, the level due to averaging would be lower than the level for an engine that had a periodic frequency at the frequency of interest. For components mounted on an engine, it is recommended that the periodic frequencies of the engine be determined and the test levels be accurately modified to represent the periodic frequency levels.

To increase the confidence of accurate analysis, more than 16 PSD's were linearly averaged together to create an average PSD. The statistical degrees of freedom (SDOF) (*8*) were determined to be—

$$k = 2 \cdot B_e \cdot T, \qquad (1)$$

where k = SDOF,

B_e = effective bandwidth, Hz,

and T = time length of signal, s.

For B_e = 2.5 Hz and T = 6.4 s and substituting into equation 2, k = 32 is obtained.

Assuming a chi-square distribution (Xk^2) and k = 32 (*7*), the confidence limits were defined as—

$$k/Xk^2_l > m/S_o > k/Xk^2_u, \qquad (2)$$

where Xk^2_l = lower limit of certainty,

m = true mean value of PSD,

S_o = computed value of PSD,

and Xk^2_u = upper limit of certainty.

Table 1 gives the confidence intervals for 90 and 99 pct confidence with k = 32 SDOF.

Table 1.—Confidence intervals of 90 and 99 pct for k = 32

Confidence	90 pct	99 pct
Xk^2_l	22.27	16.0
Xk^2_u	42.585	53.19
k/Xk^2_l	1.437	2.0
k/Xk^2_u	.7514	.6

The results in table 1 can be summarized as follows: With 99 pct confidence, m can be up to two times S_o and not less than 0.6 times S_o. Similarly, with 90 pct confidence, m can be up to 1.437 times S_o and not less than 0.75 times S_o

PSD envelopes were obtained by taking the maximum conditions experienced for each 1/3-octave filter bandwidth. The derivation of envelopes using worst-case levels is the method expected to be popular for most future MIL-STD-810 envelope construction (*4*).

Because the PSD data were in a file format that restricted further DSP, the spectrum envelopes were created in the following manner. For each particular measurement site, the spectral line containing the largest value of the PSD in each 1/3-octave frequency band from 4 to 2,000 Hz was recorded. For each 1/3-octave band, the analysis results for all trucks and orientation axes were used to compute statistical measures. The statistics computed were the mean ($\overline{PSD}$) and standard deviation (PSD_{sd}) from the maximum PSD values for each 1/3-octave band. Equations 3 and 4 give the form of $\overline{PSD}$ and PSD_{sd}.

$$\overline{PSD}(i) = \frac{1}{N}\sum_{j=1}^{N} PSD_j(i) \qquad (3)$$

and $$PSD_{sd}(i) = \left\{\frac{1}{N}\sum_{j=1}^{N} [PSD_j(i) - \overline{PSD}(i)]^2\right\}^{1/2} \qquad (4)$$

where $\overline{PSD}(i)$ = mean value of ith 1/3-octave PSD peak values,

N = number of measurements,

j = particular measurement number,

$PSD_j(i)$ = jth value of PSD for its 1/3-octave band,

i = 1/3-octave band from 4 to 2,000 Hz,

and $PSD_{sd}(i)$ = standard deviation of ith 1/3-octave PSD peak values.

Table 2 presents the alternator, cab, engine, frame, hydraulic pump, and wheel's $\overline{PSD}$ and PSD_{sd} for each 1/3-octave band. Table 3 presents the overall acceleration root-mean-square (RMS) values for a bandwidth of 4 to 2,000 Hz. Figure 1 is the mean PSD versus 1/3-octave band center frequency representation of data given in table 2. The wheel's vibrational power is concentrated below 20 Hz. The wheel vibration was due to the interaction of the tire and road as the vehicle moves. The engine's PSD was relatively distributed evenly over the entire analysis bandwidth. Peaks in the engine PSD envelope occur when common periodic frequencies existed between the various engines. The hydraulic pump PSD remained relatively constant over the 2,000 Hz bandwidth. The alternator PSD contained a high periodic component at 63 Hz and a high level over the frequency band of 500 to 800 Hz because of the rotor bar pass frequency. The frame is excited from a variety of vibration sources. The frame's PSD is comprised of power from the alternator, wheel, pump, and engine. The cab has lower PSD levels than the other locations except at 1,000 Hz.

Table 2.—$\overline{PSD}$ and PSD_{sd} in 1/3-octave band center frequency PSD peaks in machinery PSD spectra, g squared per hertz

Band, Hz	Alternator	Cab	Engine	Frame	Pump (hydraulic)	Wheel
			PSD			
4	0.016	0.0658	0.1433	0.1516	0.2186	1.449
5	.012	.031	.171	.095	.207	.231
6.3	.002	.051	.056	.182	.187	.485
8	.013	.028	.047	.296	.178	.396
10	.012	.028	.032	.168	.168	.228
12.5	.012	.029	.034	.113	.158	.204
16	.019	.034	.055	.252	.185	.285
20	.011	.029	.025	.096	.154	.109
25	.011	.033	.040	.096	.163	.122
31.5	.023	.034	.076	.102	.167	.151
40	.016	.034	.034	.055	.180	.110
50	.095	.039	.033	.290	.197	.091
63	.334	.039	.060	.196	.189	.089

Table 2.—$\overline{PSD}$ and PSD_{sd} in 1/3-octave band center frequency PSD peaks in machinery PSD spectra, g squared per hertz—Continued

Band, Hz	Alternator	Cab	Engine	Frame	Pump (hydraulic)	Wheel
			PSD—Continued			
80	0.012	0.037	0.080	0.027	0.180	0.086
100	.012	.037	.059	.040	.159	.087
125	.038	.037	.046	.028	.167	.089
160	.050	.041	.039	.028	.185	.090
200	.120	.041	.059	.027	.191	.090
250	.091	.041	.051	.032	.184	.092
315	.070	.041	.103	.030	.198	.093
400	.089	.043	.058	.046	.180	.090
500	.160	.055	.100	.045	.183	.084
630	.161	.061	.062	.041	.206	.088
800	.147	.059	.079	.027	.188	.076
1,000	.052	.140	.065	.020	.186	.069
1,250	.021	.025	.038	.022	.157	.064
1,600	.038	.036	.042	.016	.145	.066
2,000	.017	.005	.013	.009	.125	.047
			PSD_{sd}			
4	0.031	0.053	0.372	0.149	0.349	1.450
5	.039	.034	1.144	.114	.389	.586
6.3	.003	.038	.099	.214	.336	.853
8	.047	.033	.171	.560	.300	.748
10	.043	.030	.072	.452	.283	.439
12.5	.043	.032	.068	.195	.275	.476
16	.043	.036	.155	.387	.324	.583
20	.038	.033	.053	.196	.283	.211
25	.035	.036	.092	.114	.293	.246
31.5	.061	.037	.217	.126	.299	.315
40	.044	.036	.077	.062	.340	.231
50	.433	.044	.068	.058	.383	.213
63	1.577	.042	.133	1.071	.356	.218
80	.040	.039	.275	.044	.330	.227
100	.029	.044	.163	.101	.301	.234
125	.078	.044	.087	.057	.323	.225
160	.118	.051	.074	.052	.337	.237
200	.364	.052	.153	.047	.369	.242
250	.294	.051	.149	.058	.318	.250
315	.189	.050	.266	.054	.363	.246
400	.236	.055	.119	.139	.344	.245
500	.612	.077	.315	.148	.345	.223
630	.392	.083	.113	.117	.402	.254
800	.371	.077	.146	.067	.372	.218
1,000	.089	.232	.193	.044	.321	.227
1,250	.047	.038	.071	.041	.321	.226
1,600	.087	.056	.086	.026	.304	.241
2,000	.052	.028	.037	.015	.249	.174

Table 3.—Overall acceleration RMS values from 4 to 2,000 Hz

Location	A_{rmsm}, *g*
Alternator	12.05
Cab	9.99
Engine	10.57
Frame	7.88
Pump (hydraulic)	19.17
Wheel	12.79

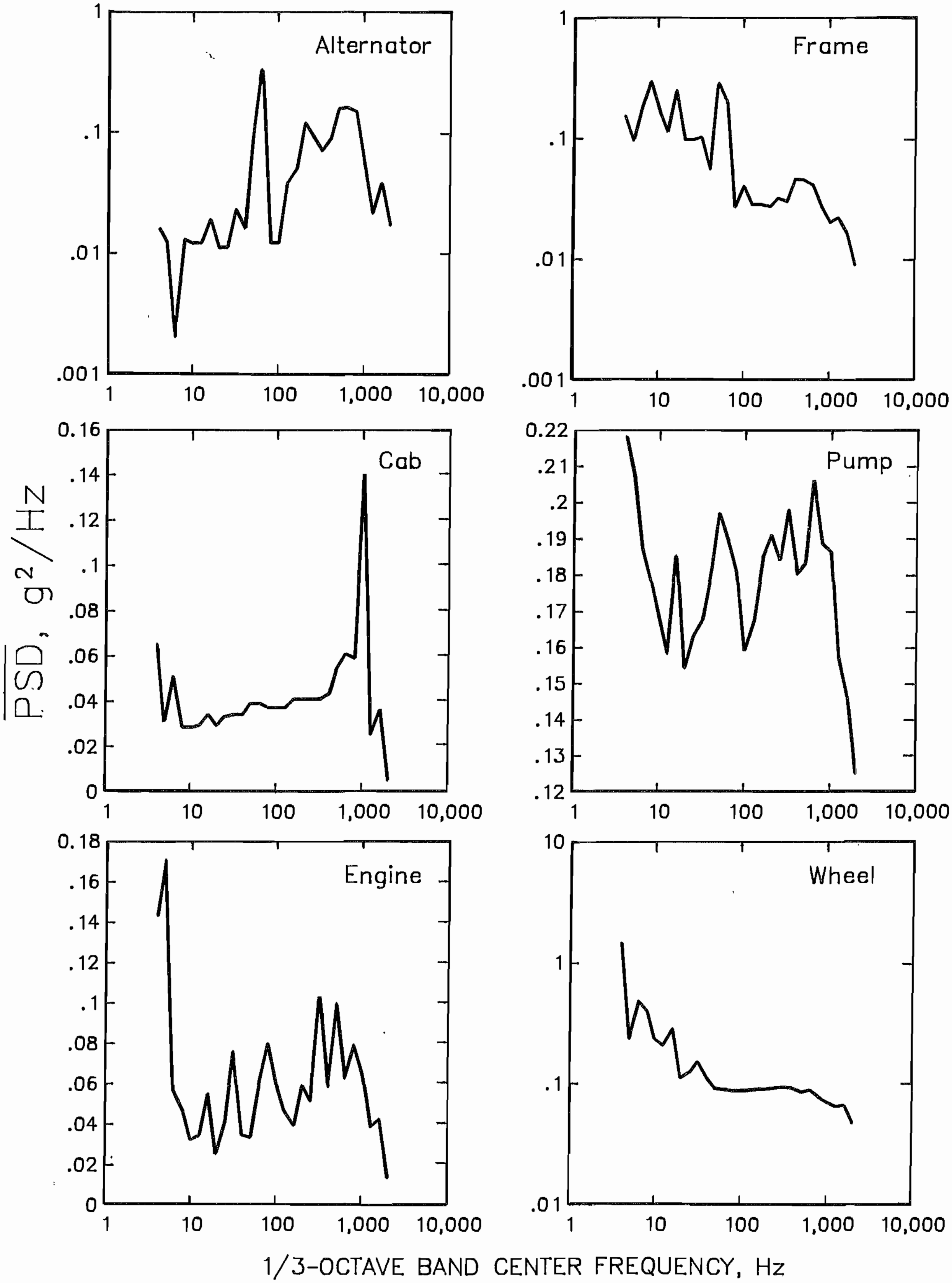

Figure 1.—$\overline{\text{PSD}}$ functional envelope at 1/3-octave band center frequency.

QUALIFICATION TESTING

It has been shown that the majority of vibration experienced by equipment in operational service is broadband in spectral content (*3*). Broadband vibration contains acceleration levels of significant magnitude over the entire frequency bandwidth of interest. For environmental vibration test purposes, random vibration effectively simulates broadband. The majority of tests in MIL-STD-810E use random vibration. MIL-STD-810E recommends using sine on random vibration testing for machinery components that consist of periodic and broadband vibrations.

Qualification testing consists of two goals. The first is to verify that the equipment will function as specified for all types of service environments it will encounter. The second is to ensure that the equipment will perform throughout its required life. To accomplish the first goal, functional tests are employed, and to accomplish the second goal, endurance tests are employed.

Functional test levels are conducted with the equipment operating and are performed at levels that are the maximum expected during normal use. Functional tests are intended to demonstrate that the equipment will function satisfactorily in the service environment. The performance of the equipment is monitored during functional tests, and deviations from specifications constitutes a failure.

Endurance testing is conducted to ensure that the equipment will perform throughout its designated life, given that the equipment receives normal maintenance requirements. During endurance testing, the equipment is not required to function to specification; however, upon completion of the test, the equipment must function to specification. A failed endurance test would occur if the equipment sustained any damage, permanent deformation, fracture, loosening of parts, or change in control settings.

Endurance tests are constructed so that equivalent amounts of fatigue are induced into the equipment as would be incurred over the normal life cycle of the equipment, but at a significantly accelerated test time. Endurance testing differs from fatigue testing in that the former does not test to failure and has a significantly smaller sample test population.

TEST PROCEDURE

TEST PREPARATION AND RECORDING

MIL-STD-810E (*3*) recommends the following preparations for the test procedure:

1. Perform life cycle analysis.
2. Identify test categories that are applicable and pertinent from the life cycle analysis.
3. Determine test conditions for each applicable and pertinent category.
4. Select appropriate test apparatus, data collection, and analysis equipment.
5. Examine the test item for physical defects, etc., and document.
6. Conduct an operational check and document the results.
7. Proceed to the required test procedure if no problems are found, otherwise correct.

A summary of information to be documented prior, during, and after the actual test is as follows:

1. Identification of test item (manufacturer, serial number, etc.).
2. Previous test history of the specified test item.
3. Inspection and test procedure, including inspection requirements, test criteria, instrumentation, data requirements, and failure criteria.
4. List of all test equipment, including vibration generating and analysis equipment, mounting arrangements, and fixtures.
5. Orientation of test item, including axes of applied vibration.
6. Location of accelerometers used to control and measure vibration.
7. Resonant frequencies, including those selected for test, as applicable.
8. Isolation characteristics, including sway amplitudes and transmissibility versus frequency.
9. Applied test levels, durations, and frequency ranges.
10. Results of all performance measurements, including overall test results.
11. Analysis of each failure and corrective action proposed.
12. Analysis bandwidth.

The tested equipment should be mounted to the shaker directly by a mounting fixture that is the same or similar to that employed in actual field usage. This is necessary to ensure that equipment mounting has a dynamic response similar to the field response.

For functional tests, the equipment should be operating as in service, and its performance recorded. Functional tests require that the equipment perform to full operation specifications.

FUNCTIONAL TEST LEVEL AND DURATION

The qualification test consists of the functional part and an endurance part. The functional testing portion is typically performed for a time duration of 1 h. The functional test envelope is constructed from the maximum levels occurring during normal work operations (table 2). The time of functional testing is equally divided before and after the endurance test (*4*).

ENDURANCE TEST LEVEL

There is a tradeoff of endurance test level versus test time. Equipment tested at lower levels require longer test times to obtain the same amount of stress as that obtained at greater levels. However, testing at lower levels reduces the risk of overtesting.

The allowable tradeoff between test level and time acceleration factor is a function of both the product and its particular application (*1*). A procedure was developed to determine test level, which weighted the relative significance of having a piece of equipment fail in the laboratory versus having it fail in the field (*6*). Two equations defining test levels that minimize the effective cost of an equipment failure are given below (*6*).

$$Pe(L) > 100[1 - (C_t/C_s)], \tag{5}$$

where $Pe(L)$ = percentile of environmental test level,

C_t = cost associated with a single laboratory test failure,

C_s = cost associated with a single service failure.

Another equation that leads to similar results is—

$$Pe(L) = 100/[1 + (C_t/C_s)]. \tag{6}$$

In practical terms, equations 5 and 6 state that components that would be relatively cheap to strengthen and/or are vital to the proper performance of the system should be tested at relatively severe levels, while components that would be more costly to strengthen and/or are less vital to system performance should be tested at more moderate levels.

Simpler systems containing few major components would be tested on the system level, not the component level. For small systems, equations 5 and 6 translate to the following: Relatively inexpensive systems that serve a critical function for proper truck performance should be tested at relatively severe levels to reduce the risk of undertesting, while systems that are expensive and perform a less critical function should be tested at relatively low levels to reduce the risk of overtesting.

ENDURANCE TEST TIME

The major goal of the endurance part of the qualification test is to induce the amount of fatigue that a piece of equipment would normally incur over its useful worklife in a fraction of that time.

Guidelines for choosing accelerated test time for endurance testing are presented in reference 4. For mobile equipment whose vibrations are broadband in nature and for which a random-type vibration test is to be performed, the relation between the exaggeration factor and test duration factor is—

$$[\overline{PSD}/PSD_t]^{3.667} = T_t/T_m \tag{7}$$

and

$$[A_{rmsm}/A_{rmst}]^{7.334} = T_t/T_m, \tag{8}$$

where PSD_t = endurance test power spectral density, g^2/Hz,

T_t = endurance test time, h,

T_m = field operating lifetime, h,

A_{rmsm} = field overall RMS acceleration, g,

A_{rmst} = endurance overall test RMS acceleration, g,

$\overline{PSD}/PSD_t$ = PSD exaggeration factor,

A_{rmsm}/A_{rmst} = acceleration exaggeration factor,

T_t/T_m = test duration factor,

subscript m = mean of peak values from field,

and subscript t = endurance test.

ENVIRONMENTAL TEST EXAMPLE

The following example was tailored as the first trial of an environmental test for the monitoring-diagnostic display panel for electronic machinery of a haulage truck. The panel is mounted on the dash inside the operator's cab. The unit is an essential component of the operating truck. It is assumed in this example that (1) failure of the unit will cause the truck to be inoperable, (2) the electronic monitoring module failure is unexpected and occurs during the work operation, and (3) the failed monitor will cause the truck to be inoperable for a period of 2 h. Typically, a mining company will have additional trucks that could be substituted for the inoperable truck. However, for this example, this factor will be left out.

The fleet will consist of five continuously operating haulage trucks. The cost to operate the fleet is $1,000 per hour or equivalently $8,000 per shift for an 8-h shift. For a fleet of five trucks operating 8 h per shift, there will be 40 h of productive work. It will be assumed that 2 h of real productivity is lost due to the failed electronic module. Over an 8-h shift, this will result in the fleet producing 95 pct of its capacity, or 5 pct nonproductivity. The cost of this lost productivity will vary significantly, depending on the specific mine where the equipment will be employed. However, mining costs can be dramatically affected by equipment downtime. For this simple example, it was assumed that the effect of loss production on mining costs can be equated to truck operating expense. This is not strictly accurate but provides a rough approximation for the purpose of this example. For an entire fleet to be unproductive for an entire shift, 40 h of nonproductivity would have to occur. Hence, the cost of nonproductivity per hour would be $8,000 per shift divided by 40 machine hours per shift, which equals $200 per hour of downtime. The cost of lost productivity for the failed electronic module is then $400, which equals 2 h downtime multiplied by $200 per hour of lost productivity. The cost of a replacement module will be assumed to be retailed at $5 00 for the mining company. The total cost per module failure to a mining company will then be the summation of the cost to replace the module ($500) and the cost of nonproductivity ($400) for a total field failure cost of $900. Assuming as a conservative figure that 10 other modules will fail on other mine vehicles during usage of the modules, the total cost of all module-related field failures would be $9,000. The cost to replace the product, assuming that it failed during a qualification test in the lab oratory, would be $500. Substituting the field cost, C_s = $9,000, and the laboratory qualification test cost, C_t = $500, into equations 5 and 6, the following per-centiles of test levels can be obtained:

$$Pe(L) = 100[1 - 500/9{,}000] = 94.4 \qquad (9)$$

and

$$Pe(L) = 100/[1 + 500/9{,}000] = 94.7. \qquad (10)$$

Increasing the conservatism to a 97.7 percentile for a normal distribution, the corresponding endurance test levels would be—

$$\overline{PSD}_t = PSD + 2PSD_{sd}. \qquad (11)$$

Values of $\overline{PSD}$ and PSD_{sd} for the cab are presented in table 2 and the resulting PSD_t values from equation 11 are presented in table 4 and shown graphically in figure 2.

The overall acceleration RMS value from the test envelope defined in table 4 is equal to A_{rmst} = 20.18 g. The overall acceleration RMS value for the cab in the field is given in table 3 as A_{rmsm} = 9.99 g. Substituting the values for A_{rmst} and A_{rmsm} and the operational lifetime of the equipment, T_m = 20,000 h, into equation 8, the estimated test time is T_t = 114.4 h. The results of this procedure will undoubtly need revisions but should be helpful as a first trial for test specification.

Table 4.—PSD_t values in 1/3-octave band center frequency for test example

Band, Hz	*PSD_t, g^2/Hz*	*Band, Hz*	*PSD_t, g^2/Hz*
4	0.172	100	0.126
5	.010	125	.126
6.3	.128	160	.143
8	.094	200	.146
10	.089	250	.143
12.5	.094	315	.149
16	.106	400	.153
20	.096	500	.208
25	.106	630	.228
31.5	.108	800	.214
40	.107	1,000	.604
50	.127	1,250	.101
63	.123	1,600	.149
80	.116	2,000	.062

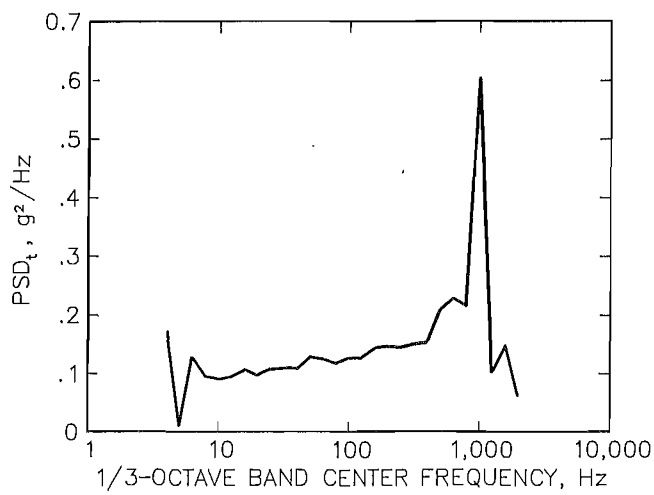

Figure 2.—Cab PSD_t endurance envelope for test example with 97.7 percentile.

SUMMARY AND CONCLUSIONS

Owing to the finite resources of the private sector, the USBM constructed electronic qualification specifications in the form of vibration environmental test envelopes for large haulage trucks. The location for envelopes are the cab, engine, frame, wheel, hydraulic pump, and alternator. The mean and standard deviations for the envelopes were constructed from the peak PSD in 1/3-octave frequency bands from 4 to 2,000 Hz. A qualification test program was developed to aid manufacturers desiring to start this type of program. An example was illustrated to show the application of this program.

Environmental testing of military equipment has been proven to be highly successful in reducing development costs and assuring high reliability in equipment performance. Highly reliable equipment increases mission success and ultimately safety to the operator. This knowledge gained from testing equipment can be applied to the commercial sector of industry with little difficulty. Use of electronic equipment to assist in the control, monitoring, communications, and diagnostics of surface mining equipment is expanding. The safe operation of surface mining machinery is increasingly relying on these electronics to function properly under all mining conditions for the lifetime of the machine. In addition to increased safety, reliable equipment increases productivity. By increasing the reliability of electronic equipment, greater safety to operators and increased productivity can be realized.

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APPENDIX.—ABBREVIATIONS AND SYMBOLS USED IN THIS REPORT

A_{rmsm}	field overall RMS acceleration, g
A_{rmst}	endurance overall test RMS acceleration, g
B_e	effective bandwidth
C_s	cost associated with a single service failure
C_t	cost associated with a single laboratory test failure
DSP	digital signal processing
i	1/3-octave band from 4 to 2,000 Hz
j	particular measurement number
k	SDOF
m	true mean value of PSD
N	number of measurements
Pe(L)	percentile of environmental test level
PSD	power spectral density, g^2/Hz
$\overline{PSD}$	mean PSD from maximum PSD values in 1/3-octave band, g^2/Hz
PSD(i)	mean of ith 1/3-octave band PSD peak values
$PSD_j(i)$	jth value of PSD for ith 1/3-octave band
PSD_{sd}	standard deviation PSD from maximum PSD values in 1/3-octave band
$PSD_{sd}(i)$	standard deviation of ith 1/3-octave band PSD mean values
PSD_t	endurance test PSD, g^2/Hz
RMS	root mean square
SDOF	statistical degrees of freedom
S_o	averaged PSD
T	time length of signal, s
T_m	field operating lifetime, h
T_t	endurance test time, h
VCO	voltage-controlled oscillator
Xk^2	chi-square distribution
Xk^2_l	lower limit of certainty
Xk^2_u	upper limit of certainty

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