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Compute Project

HDD Dynamics Common Language and Tools Phase 2: HDD Dynamics Combined Acoustic & Vibration Surrogate White Paper

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Executive Summary

The Open Compute Project (OCP) sought a follow-on to the popular OCP acoustic disturbance HDD Dynamics surrogate and continued the workgroup to define a surrogate that would reflect vibration in addition to acoustic disturbances. The following paper reviews the construction, use, calibration, and communication means for the HDD Dynamics Combined Acoustic and Vibration Surrogate.

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1 Copyright & Compliance with Open Compute Project Tenets

1.1. Copyright

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1.2. Openness

Drawings and the associated Computer Aided Design files for the HDD Dynamics Combined Acoustic and Vibration Surrogate are provided and packaged with this paper. Any third party may build the device based on this contribution.



1.3. Efficiency

Previous release of the HDD Dynamics surrogate reflected acoustic disturbance. The present release reflects additional and simultaneous measurement capability, adding vibration to acoustic disturbance measurement. In this way, much fuller picture of dynamics disturbance is possible with a single measurement versus requirement for multiple measurements. Moreover the combination of measurement capability cuts CapEx requirements by halving number of HDD dynamics surrogates required.

1.4. Impact

Rotational media, i.e., Hard Disk Drives (HDDs), remain vital in Industry for low-cost storage. At the same time, cooling through air moving devices remains ubiquitous and the air moving speeds thus dynamics disturbances to HDDs are increasing. The HDD Dynamics Combined Acoustic and Vibration Surrogate provides for a common measurement, diagnosis, and communication tool for HDD manufacturers, host enclosure designers, and other associated parties, e.g., air mover suppliers.

1.5. Scale

Drawings and the associated Computer Aided Design files for the HDD Dynamics Combined Acoustic and Vibration Surrogate are provided and packaged with this paper. Any third party may build the device based on this contribution. Depending on a user's deployment environment, multiples of the devices may be deployed simultaneously or a single device may be run sequentially.

1.6. Sustainability

Primary impact is in reduction of test devices needed in data collection and/or communication of dynamics disturbances among parties interested in HDD Dynamics verse previous means whereby several different measurement schemes were built and used in measurement and translation. Materials and equipment used in the HDD Dynamics Combined Acoustic and Vibration Surrogate are clearly called out in the paper and drawings. Finally, an indirect benefit of the device is in identification of reduced air mover speeds that result not just in HDD dynamics benefits but also power savings for the same cooling.

2 Introduction

Hard Disk Drives (HDDs) remain ubiquitous in Industry, and their performance can degrade during acoustic or vibration disturbances, especially as air mover speeds increase to keep pace with cooling needs of components in IT equipment. If the reader is not already familiar with the topic, it is recommended that they first review our OCP Storage HDD Dynamics workgroup's 2021 paper entitled "HDD Dynamics Common Language and Tool: Phase 1 – Acoustical HDD Surrogate White Paper." The problem statement and approach taken by the workgroup to provide tools and communication schemes to facilitate dialog and analyses of dynamics challenges are discussed in Section 2 of the aforementioned paper.

While acoustics is presently the dominant mechanism in HDD Dynamics disturbance and was therefore the focus of the Phase 1 paper, the interest to represent the complementary vibration aspect drove definition and objectives for Phase 2 efforts. In Phase 2, the workgroup developed a new tool that adds vibration capabilities to acoustic measurement capabilities in the same test device. It is thus aptly named "HDD Dynamics Combined Acoustic & Vibration Surrogate."

3 HDD Surrogate Usage Models

Usage models for the Combined Acoustic & Vibration Dynamics HDD are the same as those as described in Section 3 of the Phase 1 paper. In some cases, transmitted vibration may be suspected to dominate HDD dynamics disturbance. The added vibration measurement capability of the new surrogate may therefore prove especially helpful.

A key application is assessment of a host enclosure before it is operational but when its air movers can be controlled to different speeds. In this case, surrogate measurements provide insight into excited modes of the enclosure's mechanics. Alternatively, the surrogate may detect structural modes when a host enclosure is mounted onto a shaker through connecting rack fail fixtures and the shaker excitation is varied.

When necessary and when an operational host enclosure capable of supporting I/O operations is available, surrogate measurements may be made with adjacent drives idle and seeking. Surrogate measurements may then provide insight into vibration transmission through the enclosure under normal operating conditions. Impacts of chassis mounting points or slot adjacent drive excitation may also be assessed.

4 Hardware Requirements

Mechanical hardware, microphones, and data acquisition systems were described in Section 4 of the Phase 1 paper. In Phase 2, these are reused but the “HDD Dynamics Combined Acoustic & Vibration Surrogate” contains an altered structure to house accelerometer sensors and to accommodate other vibration design considerations described later. The new surrogate hardware and accelerometers are discussed in this section, while the recommended microphone remains GRAS 47BX ¼” CCP Flush mount microphone (7.5 grams, 1.6 mV/Pa, 4-25 kHz, +/-1 dB), as shown in Figure 1.

4.1 Accelerometers

High-quality fine-resolution accelerometers are recommended. Such devices must support sensitivities of at least 100mV/g and be capable to measure frequency content up to at least 5 kHz. One example of a device that meets these requirements is the Amphenol/PCB Piezotronics ICP Accelerometer model #352A24, as shown in Figure 1. Six accelerometers are required to resolve six degrees of vibration freedom in the HDD Dynamics Combined Acoustic & Vibration Surrogate, and they must be installed in a specific array described later in this paper. Retail cost of each accelerometer is approximately \$500 USD, so the total cost of the six accelerometers is approximately \$3,000 USD.



Figure 1: Example of Recommended Accelerometer and Microphone

4.2 Combined Surrogate Structure and Enclosure

Hardware requirements and electro-mechanical design details for the HDD Dynamics Combined Acoustic & Vibration Surrogate are described in this section. The drawing associated with the design is linked to this paper in the OCP Storage site and reflects three main sections of the surrogate: Body, Top Cover, and Connector. The surrogate is designed to have the same size,

shape, and mass as a 3.5" HDD, so that it may be used in situ and experience the same disturbances as an actual HDD. The surrogate's physical dimensions and shape are therefore governed by SNIA SFF 8301 specification as 101.6mm x 147.0mm x 26.1mm. While the mass of modern HDDs may range from about 640g to 750g, at the time of writing, one mass value has been selected: 680g (inclusive of sensor masses).

To permit attachment of any HDD carrier of interest, the side and bottom mounting holes are same as those of production HDDs. The Top Cover attaches to the Body through twelve stainless steel M2.5 x 0.45 – 6H socket head cap screws (SHCS), using a torque of 7 kg-cm (6.1 lbf-in). Typical HDD top cover screws are compatible in size and may also be used, but such screws will sit more recessed in the surrogate cover hole than SHCS.

Under certain situations, such as if there is interference with the carrier, modifications to surrogate dimensions may be required to fit the particular carrier configuration. When this occurs, the differences in mass and inertia should be ascertained to determine impact to surrogate measurements. Accordingly, vibration calculations described in this paper may need to be altered. Use of certain drive carrier designs may require modification to allow the sensors' cables to pass through to the outside of the system, usually achieved by snipping some front grids of carrier.

The frequency range in which consistent vibration measurement result occurs where response of the surrogate is mass controlled, that is, below the fundamental resonance of the HDD Dynamics Combined Acoustic & Vibration Surrogate. Above resonance, the response is prone to unit-to-unit variations arising from structural joint damping variations across surrogate units. The workgroup has observed and documented that structural vibration transmission relevant to HDD dynamics spans to 3000 Hz (while, as related in Phase 1, acoustics relevant to HDD dynamics spans to 20000 Hz).

The surrogate has therefore been designed and validated to demonstrate resonance at a frequency greater than 3000 Hz. Because mass loading of multiple sensors can tend to reduce the resonance frequency of the surrogate, the geometry and especially the number and location of screws were carefully planned, as shown in Figure 2. Finite element analysis (FEA) simulation applied to an early surrogate design with six screws revealed resonance frequency of

2900 Hz, and when the number of screws was increased to twelve, the simulation indicated resonance frequency of 3480 Hz and thus met the resonance frequency requirement $> 3000\text{Hz}$.

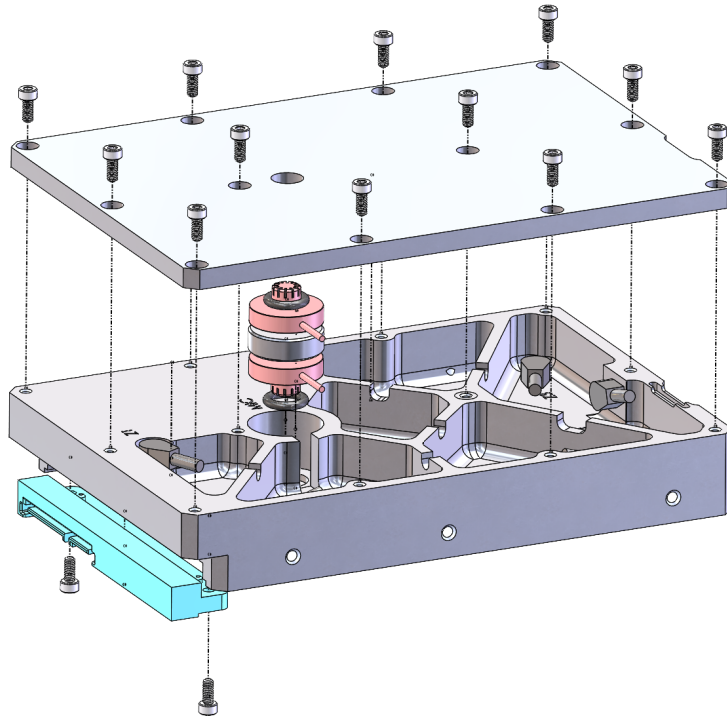


Figure 2: Locations of screws, microphones, and accelerometers within the surrogate enclosure

Primarily because the mass of the voice coil magnets and plates varies across HDD manufacturers and models, the center of gravity of a 3.5" HDD is generally offset from the geometric center of the HDD. The surrogate's centroid is offset from geometric center as shown in Figure 3.

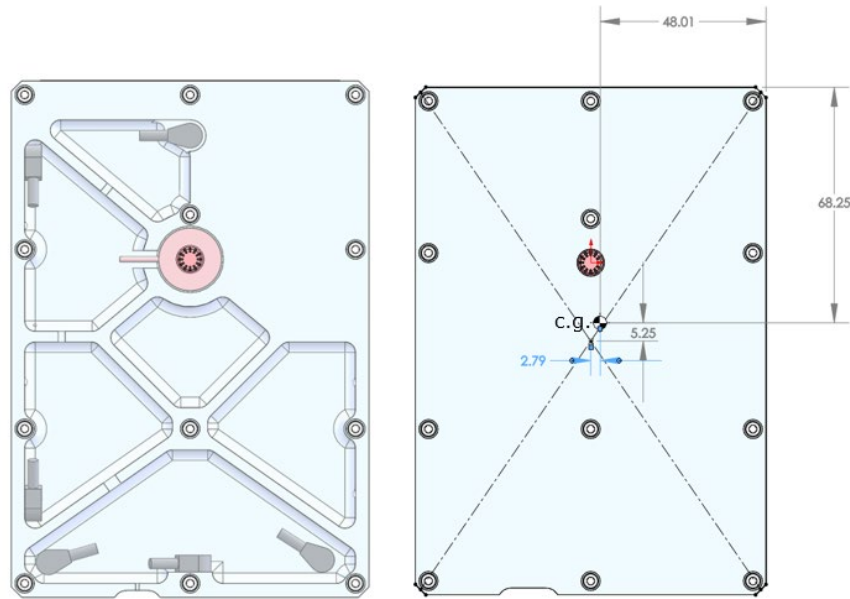
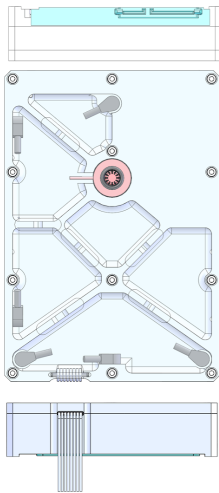


Figure 3: Center of gravity is not at the geometric center of the surrogate

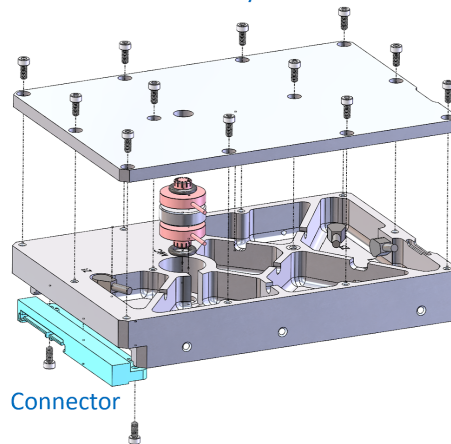
A connector was designed to provide as stable a physical connection to the system under test as that on an actual HDD. Although connector shape and pin-out of HDDs are well defined, HDD manufacturers tend to use proprietary connector components to best integrate to their own PCBs and rest of HDD. The workgroup did not therefore choose a single commercially available standardized 3rd-party “HDD side” connector. Instead, the workgroup defined a component that must be fabricated via 3D printer. In an initial evaluation, the connectors were printed on 3D Systems with PB-10 material.

As with the Phase 1 surrogate, CAD files are provided for the Phase 2 HDD Dynamics Combined Acoustic & Vibration Surrogate at the OCP Storage group website. The cost of materials and labor to generate the Top Cover, Connector, and Body (and excluding cost of sensors), as shown in Figure 4, is estimated at \$2,000 USD.

Sensors & Connectors

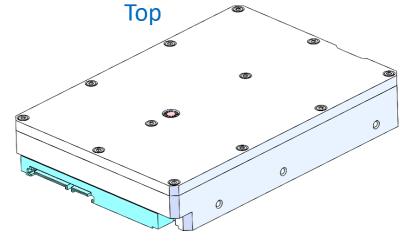


Assembly

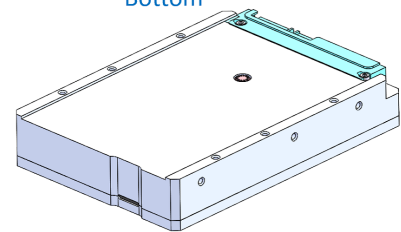


Connector

Top

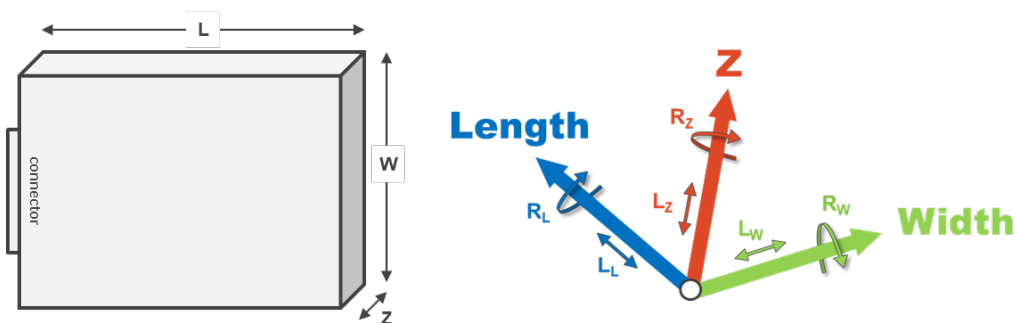


Bottom


Figure 4: Excerpts from Drawing representing Top Cover, Connector, Body, and Sensors.

4.3 Vibration Axes Definitions

Installation of a HDD and thus the corresponding surrogate into a host enclosure is dependent on orientation of HDD slots in the host enclosure under test. In order to maintain consistent means of communication, the workgroup defined axes of motion specific to HDD Dynamics and related to the rigid body motions of the surrogate. As shown in Figure 5, the “Length” or “L” axis is parallel to the long side of the HDD, the “Width” or “W” axis is parallel to the short side of the HDD, and the “Z” axis is parallel to the thickness of the HDD. The six corresponding degrees of freedom are rotational (R_L , R_W , and R_Z) and longitudinal (L_L , L_W , and L_Z).


Figure 5: Definitions of Vibration Axes and Corresponding Degrees of Freedom

4.4 Mass and Inertial Properties

Mass properties for the HDD Dynamics Combined Acoustic & Vibration Surrogate without the accelerometer and microphone cables are listed in Table 1.

Table 1: Surrogate mass and inertial properties

Property	Value	Units
Mass	695	grams
I_{xx}	671,881	grams-mm ²
I_{yy}	1,302,305	grams-mm ²
I_{zz}	1,884,213	grams-mm ²

4.5 Accelerometer and Microphone Locations

A total of eight sensors are designed into the HDD Dynamics Combined Acoustic & Vibration Surrogate. Locations are specifically indicated in CAD, and are to be marked / letter punched into the surrogate Body, shown in Figure 6. Six accelerometers are purposefully located to maximize resolution to the six degrees of freedom. Two microphones are in the same location and are same types as in the Phase 1 surrogate, namely a top surface microphone and a bottom surface microphone.

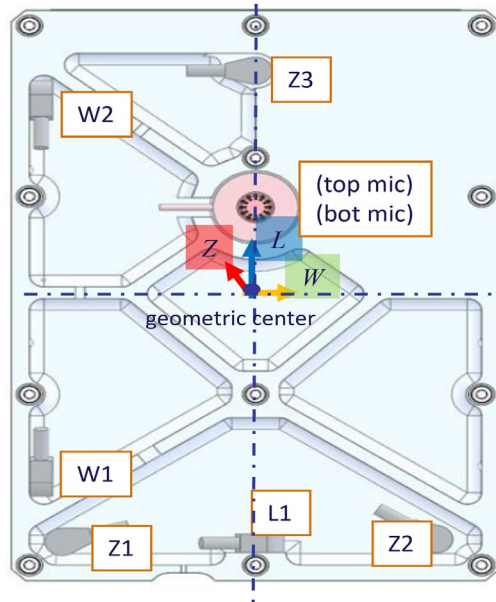


Figure 6: Microphone and Accelerometer locations.

4.6 Microphone Installation: Clarifications and Additions

While the locations of the microphones in the Phase 2 HDD Dynamics Combined Acoustic & Vibration Surrogate are the same as those in the Phase 1 surrogate, the workgroup calls out clarifications and additions regarding installation of the microphones. One port hole in the Top Cover and another in the surrogate Body accommodate high-resolution flush-mount microphones described in Phase 1. Recesses around the port holes accommodate O-Rings between the microphone and the Top Cover. The O-Rings compress upon microphone installation and isolate, secure, and center the microphones within their port holes, as represented in Figure 7. Care should be taken to ensure microphones are snug and slightly recessed from a purely flush mount condition, in order to accomplish the following: i) reduce the chance of damage to the microphones and ii) reduce introduction of wind noise around the microphone. The workgroup recommends that the microphones be calibrated prior to installation to the surrogate.

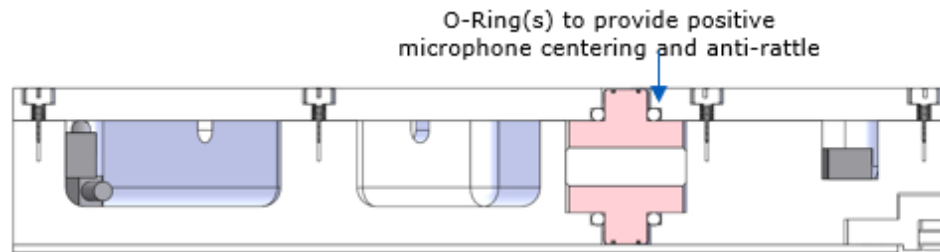


Figure 7: Side View of surrogate showing O-Ring compressing and correctly positioning the microphones.

4.7 Strain Relief and Care for Sensor Cables

Cables to the sensors are fragile, and caution should be exercised when manipulating them. While the accelerometer cables can be replaced independently, the microphone cables cannot be replaced, and appropriate care can reduce risk of damage. HDD Surrogates are never intended to be carried or handled by the sensor cables. The safe method of handling the surrogate is by firmly holding the aluminum enclosure.

As may be seen in Figure 8, each accelerometer cable has two connections: one at the accelerometer itself and another at the end that connects to a cable that runs to the data acquisition system. Compared to the microphone cable interface, the 3-56 interface of the accelerometer cable loosens fairly easily. Prior to installation of the accelerometers to the surrogate, the tightness of the connections and integrity of signal should therefore be confirmed.

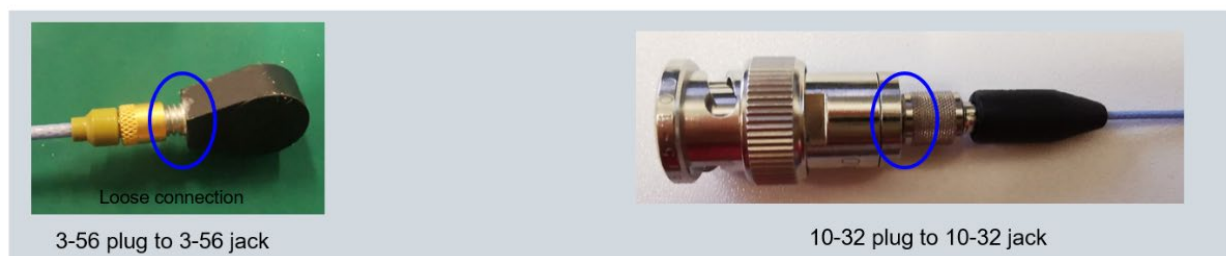


Figure 8: Connections to accelerometer cables should be tight

At the exit of the cable from the microphone, an edge in the Body structure may rub against the cable. While the CAD represents a rounded edge, the reader may wish further to reduce risk of wear to the cable. Tape may be used as shown in Figure 9.

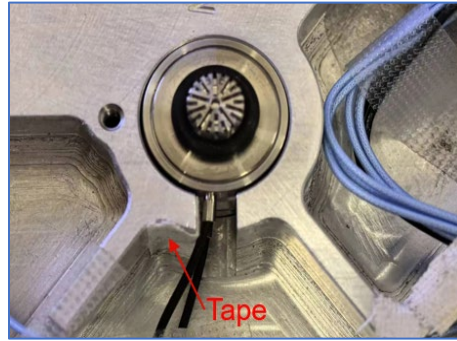


Figure 9: Smoothing of edge at exit of cable from microphone may be enhanced with tape.

While it is not fool proof, a strain relief mechanism is designed into the surrogate to help prevent accidental damage to sensor connectors. As demonstrated in Figure 10, the strain relief is comprised of two safeguarding features: 1) all sensor cables are first internally routed in an additional loop around the mated slots provided in the Top Cover and Body, 2) as they exit the enclosure, the sensor cables are aligned next to each other and pressed flat between two rubber strips made from O-ring material.

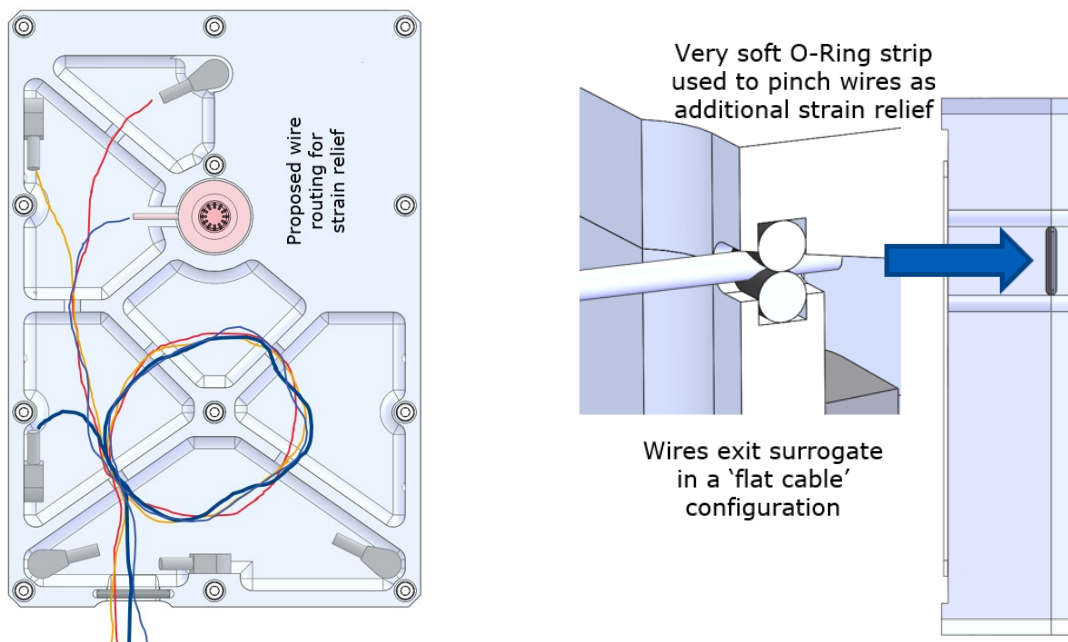


Figure 10: Two strain relief features to safeguard the sensor cable connection

As portrayed in Figure 11, the workgroup considered a flat cable bundle to be preferable to a round bundle, because it allows easier bending around tight radius requirements encountered in

dense HDD-laden enclosures and almost ubiquitous use of HDD carriers. Some provisions or minor modifications may be required in larger systems, to safely pass the microphone cables from HDD slots to data acquisition gear located outside the chassis.

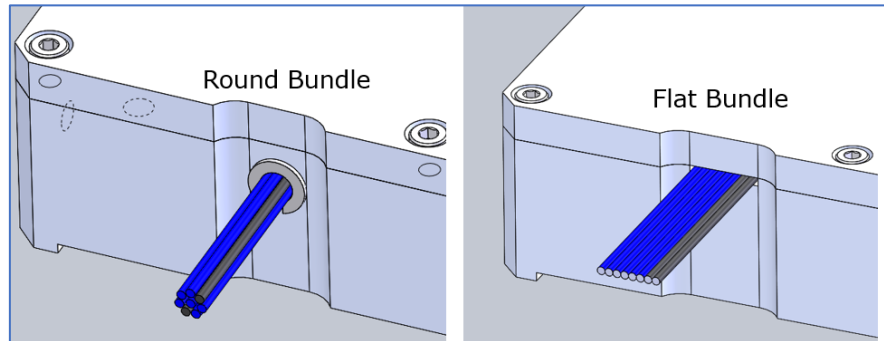


Figure 11: Sensor cable exit options: round-bundle vs. flat-bundle

Because there are eight cables in the cable bundle, some method should be used to hold the cables together from the surrogate exit to the data acquisition system. Since the surrogate cable may need to pass thru small openings or captivated between close surfaces, use of cable bundling material should be selected with minimum thickness. Masking tape or the equivalent may be used at intervals down the length of the bundle to keep the cables together.

Zip ties are not recommended for cable bundling. During an initial check of the six accelerometers and two microphones prior to taking data, the Z2 accelerometer response was found to be significantly different than that of the other five accelerometers (see Figure 12). The accelerometer was removed from the surrogate and checked with a new cable and found to have acceptable response. Several areas along the cable where the zip ties were located were noticed to have been indented, and the zip ties were determined to have compressed the cable to the point of failure.

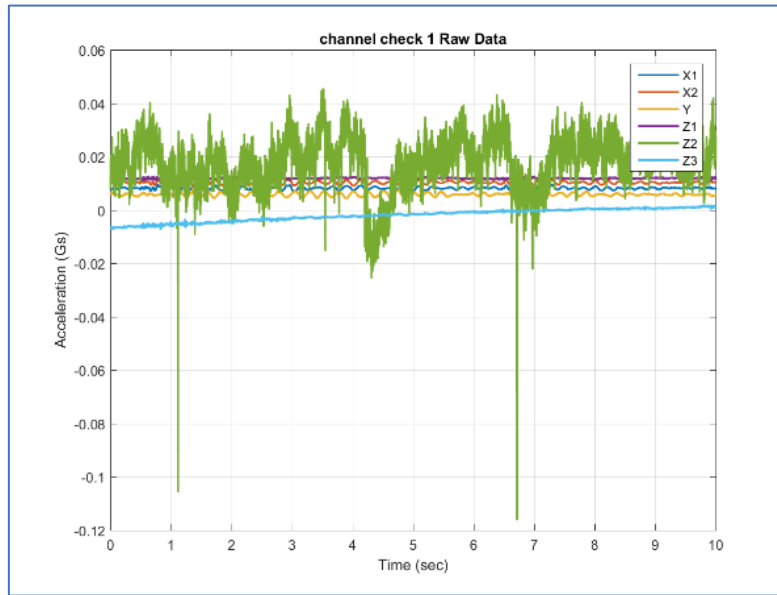


Figure 12: Accelerometer output channel check that indicated a cable issue

4.8 Data Acquisition Systems

Based on data review, experience, and focus on intended usage, the workgroup determined that the data acquisition system should be similar to that required for the Phase 1 surrogate with the addition that it must accept a minimum of eight channels of input (two for microphones and six for accelerometers). Such gear should also support 24-bit, provide greater than or equal to 40kHz resolution per channel, and allow attachment of the defined sensors' cable connectors. A non-exhaustive survey of some data acquisition systems currently on the market and meeting the minimum requirements is provided in Table 2. The approximate retail cost for this gear falls in the range of \$4,500 to \$17,000 USD.

Table 2: Examples of Data Acquisition Systems for HDD Dynamics Combined Acoustic & Vibration Surrogate

Vendor	HEAD Acoustics	Data Physics	Data Translation	National Instruments	National Instruments
Model Hardware	SQuadriga III	DP901-6 (2)	DT9857E-8-xAO	NI-9231/ cDAQ-9171	NI-9234 (2)/ cDAQ-9174
Retail Price (Hardware)	\$ 15,400.00	\$ 23,720.00	\$4,369.00	\$ 4,804.00	\$ 6,608.00
Framework/ Chassis	N/A	N/A	N/A	\$ 970.00	\$ 1,483.00
Total	\$ 15,400.00	\$ 23,720.00	\$4,369.00	\$ 5,774.00	\$ 8,091.00
Analysis Software	Need to purchase	DP930-10/23	QuickDAQ (free), Open Layers (free), DASYLab, LabVIEW, MATLAB	User can create in- house program for analysis (e.g. Matlab, LabView)	User can create in- house program for analysis (e.g. Matlab, LabView)
Cost (Software)	\$ 1,984.65	\$ 4,930.00	\$ -	\$ 1,750.00	\$ 1,750.00
# Channels	8 Channel/ 24 bit	12 Channel/ 24 bit	8 Channel/ 24bit	8 Channel/ 24bit	8 Channel/ 24bit
Resolution/ Channel	51.2kHz	40kHz	105.4kHz	51.2kHz	51.2kHz
Voltage Range/ Auto Range	+/-5.0V (Auto Range)	+/-0.1V, 1.0V, 10.0V (Fixed Voltage)	+/-1.0V, 10.0V (Fixed Voltage)	+/-5.0V (Fixed Voltage)	+/-5.0V (Fixed Voltage)
Dynamic Range	97dBA	120dB	105dBFS	102dB	102dB
SNR (signal-noise ratio)			95dB	97dB	97dB
ICP supply	YES	YES	YES	YES	YES
Power	Battery-6hr (Portable)	Power Adaptor	Power Adaptor	Power Adaptor	Power Adaptor
Picture					

5 Measurement

5.1 Test Environment & Setup

HDD Dynamics surrogates may be used for measurements in host enclosures on benchtop or in rack-mounted configurations. For benchtop configurations, placing the chassis on mounts that physically isolate the bottom of the host chassis from the benchtop is recommended. If this is not done, the benchtop surface may dampen or otherwise alter vibration transmission paths and yield misleading and/or nonrepeatable results.

Broadband sound pressure level (SPL) that results in disturbance sufficient to cause performance degradation has been observed generally to exceed 100 dB, re 20 μ Pa, at the

HDD. For readers unfamiliar with acoustical terminology, sound pressure level is given in terms of the logarithm of the ratio of acoustic pressure to a reference pressure, or 20 micro-Pascals in air. The units are decibels (dB). If your ear were at the location of the HDD undergoing performance degradation, what you hear might be as loud as a jack hammer or a chain saw. The test environment therefore need not be quiet and moreover, an acoustical test chamber is generally not required.

HDD dynamics sensitivity may increase with frequency, and so, as discussed in the Phase 1 paper, background levels and frequency content should be documented before each test. In addition, putting limits on background noise may aid in ability to correlate acoustic frequency signatures observed at the surrogate to specific sound sources internal or external to the host enclosure. The same holds true for limiting potential sources of external vibration in the test environment.

As was reviewed in the Phase 1 paper, the acoustic time signal should be processed into 1/3rd octave unweighted sound pressure level from 100Hz to 20kHz, and then rounded to the nearest integral decibel. Each 1/3rd octave unweighted sound pressure level should be at least 10 dB above the background noise. To validate this, the result of a test conducted with the host system powered down is compared to the acoustic measurement from the HDD Dynamics surrogate. If the difference is smaller than 10 dB, then the test environment should be changed. This can be done by moving the test setup to a quieter space, placing barriers around the host chassis, turning off equipment that is contributing to the background frequency content of concern, etc.

It is recommended that all slots in the host enclosure be filled with HDDs. This can help in reflecting dynamics disturbances related to airflow as well as provide additional vibration excitation from adjacent drives that is comparable to a real-world deployment. If the entire host enclosure cannot be filled with HDDs, the slot population should be documented, and attempts should be made at least to fill the entire row closest to the air movers and then the 2nd row from the air movers, etc.

Before starting measurement, the integrity of the sensors in the HDD Dynamics surrogate should be checked. For the microphones, a background measurement can be made (outside the host chassis), and the individual microphones can be compared against an expected or

historical background level. The accelerometers can be checked by manipulating the surrogate by hand. With the surrogate in hand, 18 back and forth motions should be done in a twenty second capture; 6 motions each in W, L and Z directions. Check the individual sensor output (example shown in Figure 13) to confirm the comparable direction and amplitude. Any outliers should be checked for integrity of connections or other sensor issues.

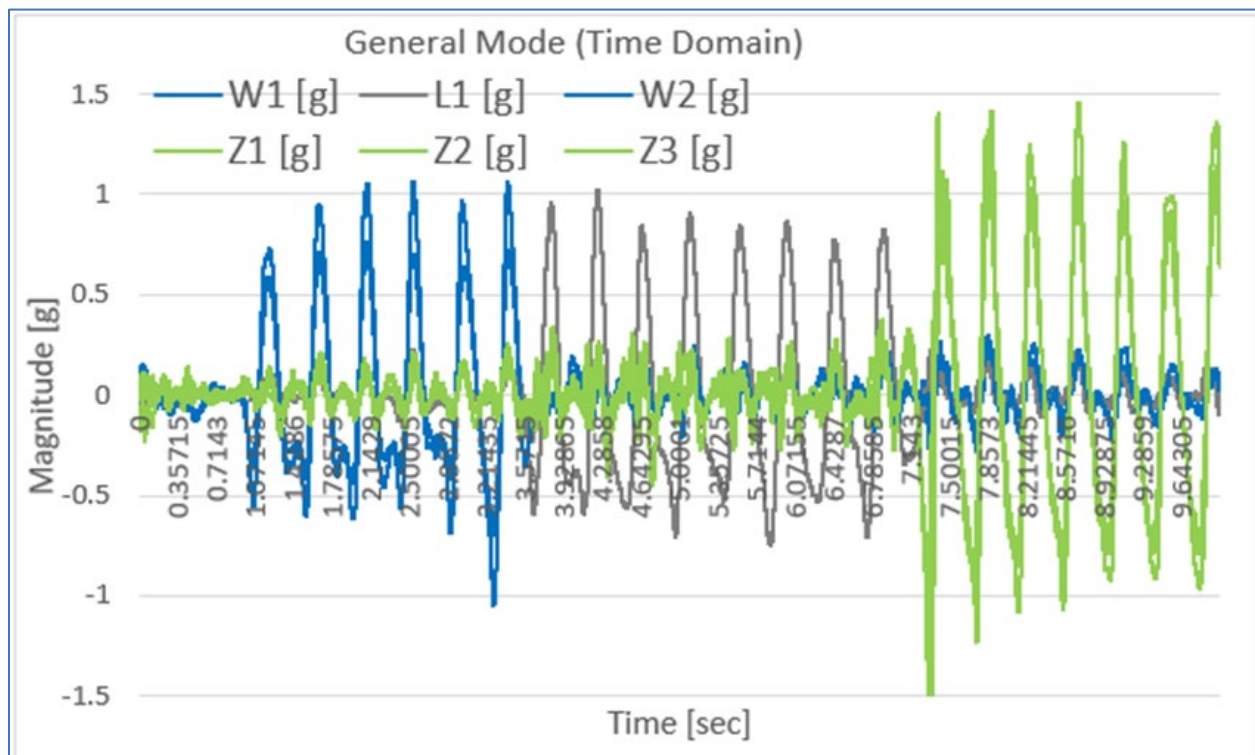


Figure 13: Pre-test vibration sensor check for different vibration directions

5.2 Measurement locations and duration

The HDD slots of interest should be agreed on between the generators and consumers of data from the HDD Dynamics surrogate. If the HDD slot requires a carrier, then it should be attached to the surrogate. In many cases and as discussed in Section 4.2, the carrier may require modifications to allow the cable bundle to pass thru to reach the data acquisition system. Care should be taken to minimize changes to the carrier structure that may change the dynamics.

The surrogate should be installed into each HDD slot of interest, and then the suspected sources of dynamics disturbances should be energized, for example, air movers set to speeds

of interest. Measurement time per HDD slot and test condition should be at least twenty seconds. Data recorded from all sensors should be saved independently, (i.e., not combined, averaged, etc.). Retaining the time history for each sensor allows for post-processing through any specific analyses desired or required for development investigation, i.e., outside the scope of this paper.

During measurements with the HDD Dynamics surrogate, dependency on air mover speeds may be characterized. Dependency for different adjacent HDD conditions (i.e. idle or seek) may also be characterized. An example adjacent seek condition could be a 4K Random for all HDD slots.

5.3 Vibration Time Signal Data from Surrogate

The time signals from the six accelerometers should be combined in accordance with Table 3. Time must be retained in the initial processing step to maintain phase information. To increase accuracy, moment arms A, B, and C should be measured directly from positions within the surrogate. Calibration is discussed in **Appendix B**.

Table 3: Vibration calculations, where $g = 9.81 \text{ m/second}^2$, and HDD dynamics dimensions $A=0.120 \text{ m}$, $B=0.075 \text{ m}$, and $C=0.092 \text{ m}$,

$LW(t) = (W1(t) + W2(t)) / 2$	$RW(t) = (Z3(t) - (Z1(t) + Z2(t))) / A * g$
$LL(t) = L1(t)$	$RL(t) = (Z1(t) - Z2(t)) / B * g$
$LZ(t) = (Z1(t) + Z2(t)) / 4 + Z3(t) / 2$	$RZ(t) = (W1(t) - W2(t)) / C * g$

5.4 Vibration Frequency Domain Data

The vibration time domain signal should be converted to frequency domain for purposes of comparison to thresholds intended to correspond with HDD throughput performance. The parameters listed in Table 4 should be used in the transformation of all six vibration degrees of freedom. The transformation may be carried out through automated signal analysis software or through code written to do so. Example output are shown in Figure 17 and Figure 18. For a discussion of amplitude and energy correction and FFT averaging, see Appendix A.

Table 4: Parameters for frequency domain transformation of time domain vibration signals.

When Used	Parameter	Value
Recording data	Sample Rate (Fs)	>40000 Hz ¹
Recording data	Capture Time	10 sec minimum ²
Analysis	Time to Frequency function	Power Spectral Density (PSD) ³
Analysis	DFT/FFT number of points (nfft)	Selected for Δf of 6 +/-1 Hz ¹
Analysis	DFT/FFT frame averaging	Welch's method or equivalent ³
Analysis	Window Function	Hann ³
Analysis	Overlap	50% ³
Analysis	Compensation	Energy ³
Analysis	PSD units	rms ³
Analysis	Vibration PSD input traces	Calculated 6 DOFs using time traces
Analysis	Acceleration frequency bandwidth	30-3000 Hz

Notes:

1. Common combinations are $F_s = 48000$ Hz and $nfft = 8192$ points for $\Delta f = 5.86$ and $F_s = 40000$ Hz and $nfft = 6400$ for $\Delta f = 6.25$ Hz.
2. Common times are 10 seconds and 20 seconds.
3. See Appendix A for a discussion of time domain to frequency domain conversion including energy and amplitude compensation and frame averaging to reduce noise

6 Recommended Report Template & Information Flow

Recommended report template and information flow were described in Section 5 of the Phase 1 paper and also hold for the “HDD Dynamics Combined Acoustic & Vibration Surrogate.” For completeness they are repeated in this paper.

Recommended communication flow among parties interested in harnessing HDD Dynamics information is shown in Figure 14 and Figure 15. Important information includes description of sensors, data acquisition system, host system variables, HDD slot(s) tested, background levels, and test levels. Parties may choose to provide additional information that may include guideline thresholds, defined specifications, or engineering areas of concern.

From Phase 1, example acoustical data report template is repeated in Table 5 and with contrast to example acoustical threshold guidance in Figure 16.

In the present paper we provide a similar template for HDD Dynamics vibration data. The recommended data template for vibration is shown in Table 6 and plot templates are shown in Figure 17 and Figure 18. Note one plot uses a linear X axis and one uses a log X axis as examples of different ways to emphasize the data. In addition to the test parameter information described from Phase 1, keeping a record of the table of sensor sensitivities as in Table 7 is recommended.

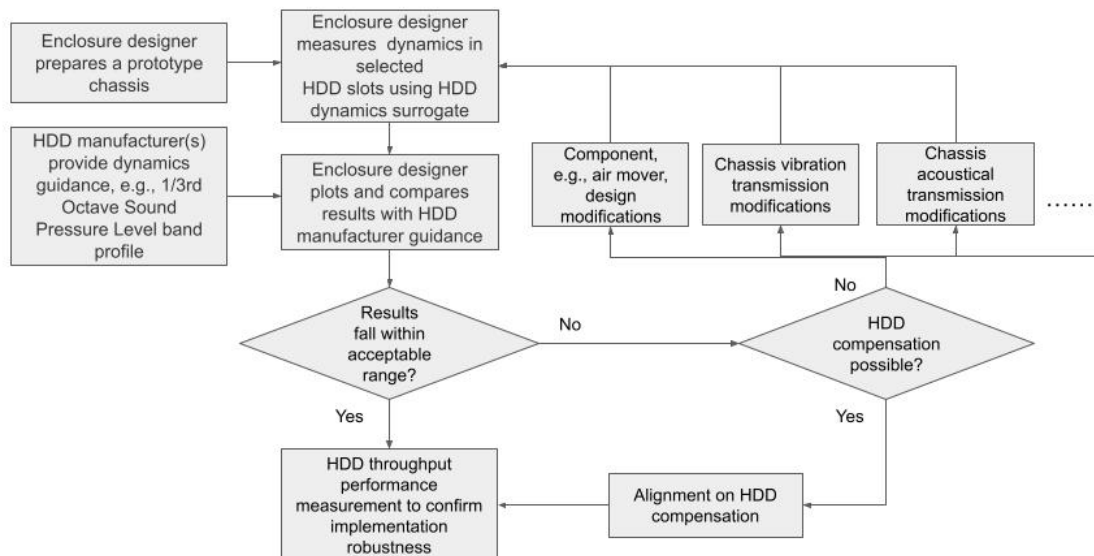


Figure 14: Recommended communication flow between HDD manufacturer and enclosure designer

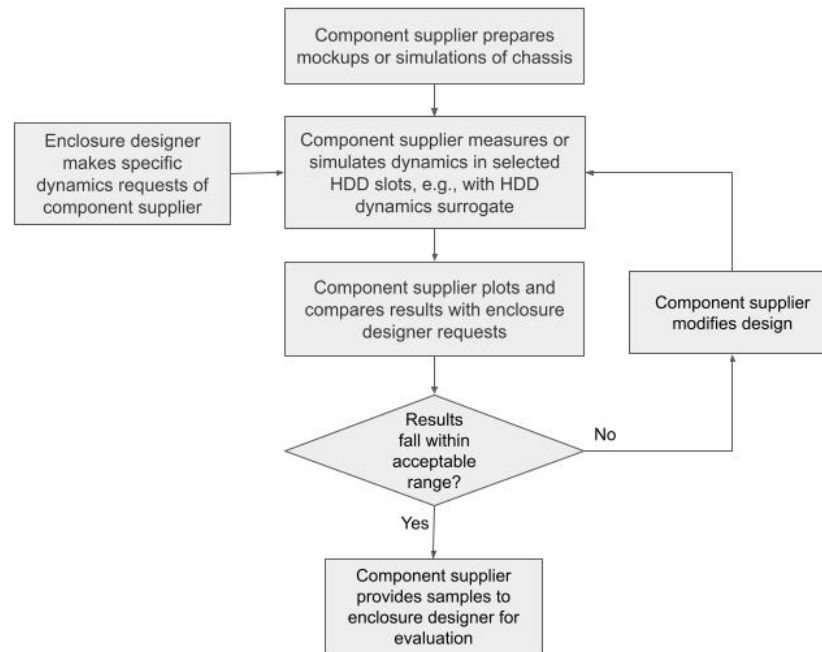


Figure 15: Recommended communication flow between enclosure designer and component supplier, e.g., air mover supplier

Table 5: Recommended report template and sample data.

Microphone Type A, Data Acquisition System B, Test Date, Test Contact			
Center Frequency, Hz	Background	Enclosure X1, Fan Y1 at Z1 RPM, Slot W1	Enclosure X2, Fan Y2 at Z2 RPM, Slot W2
100	74	86	84
125	74	87	84
160	74	89	84
200	74	89	88
250	71	90	89
315	74	92	88
400	70	89	89
500	69	86	88
630	62	85	87
800	62	98	97
1000	62	93	96
1250	69	94	96
1600	71	103	96
2000	68	93	91
2500	64	94	93
3150	61	97	93
4000	58	95	93
5000	54	97	93
6300	54	94	94
8000	50	91	85
10000	52	87	81
12500	48	85	78
16000	44	81	73
20000	40	76	69

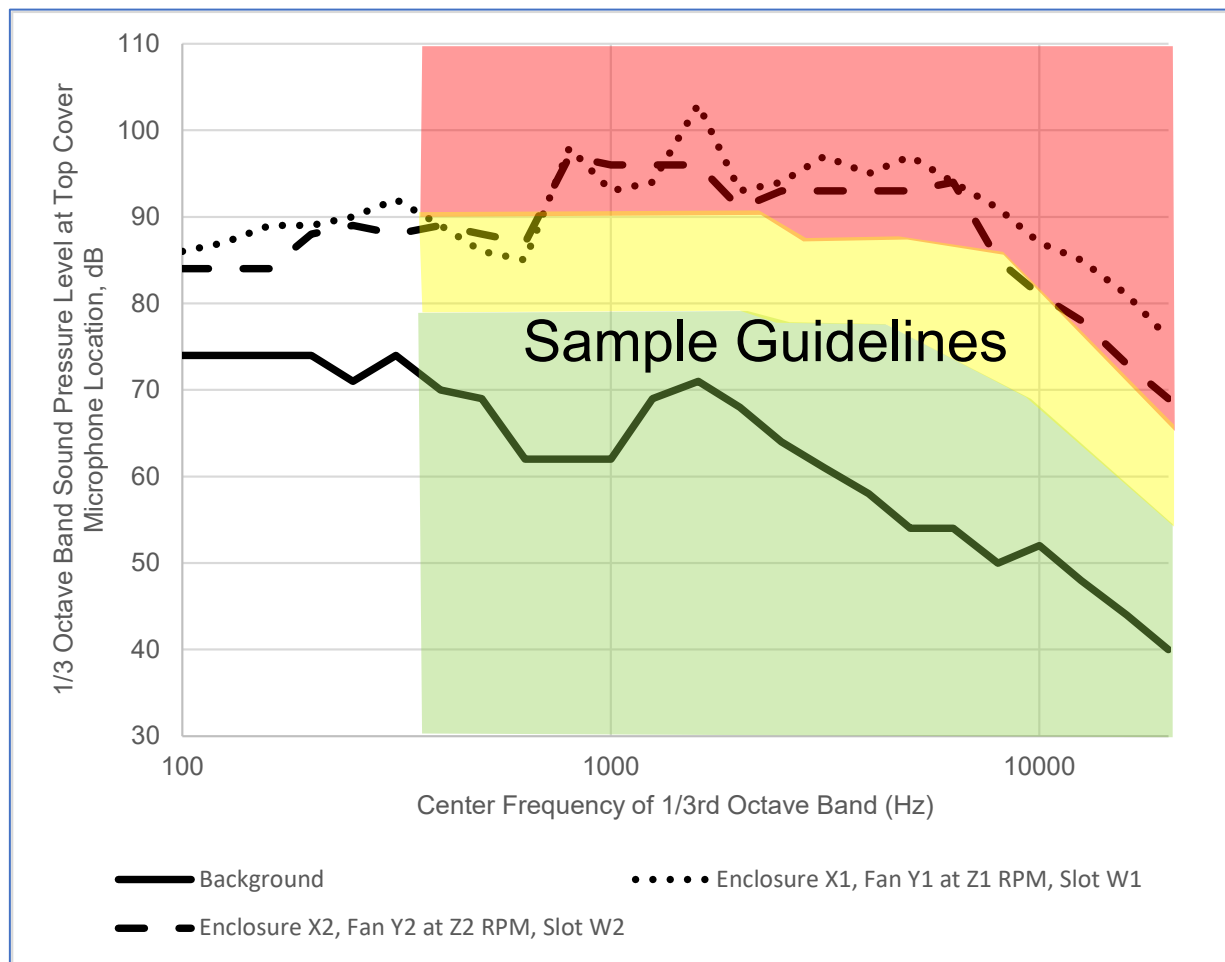


Figure 16: Plot of sample test data overlaid on risk coloration scheme of sample guidelines. The 1/3rd octave band sound pressure level data represented by the dashed and dotted lines reside mostly in the red or high risk zone. Guidelines may vary by HDD manufacturer, model, etc.

Date						
Host Chassis	Enclosure1	Enclosure1	Enclosure1	Enclosure1	Enclosure1	Enclosure1
Fan Make/Diameter						
#Fan/Enclosure						
#Drive/Enclosure						
Fan%						
Slot#						
Adjacent Drives	4K Random	4K Random	4K Random	4K Random	4K Random	4K Random
Freq	Linear LVw	Linear LVI	Linear LVz	Rotational LVw	Rotational LVI	Rotational LVz
Hz	[g^2/Hz]	[g^2/Hz]	[g^2/Hz]	[(rad/sec^2)^2/Hz]	[(rad/sec^2)^2/Hz]	[(rad/sec^2)^2/Hz]
6.25	6.49E-06	1.49E-06	5.74E-08	4.84E-04	1.01E-02	6.72E-01
12.50	1.16E-08	6.55E-09	0.00E+00	9.76E-06	2.94E-05	2.94E-04
18.75	4.60E-09	1.13E-08	6.51E-09	3.19E-05	3.37E-05	8.57E-06
25.00	2.19E-09	1.71E-08	6.17E-10	4.92E-05	1.79E-05	1.96E-05
31.25	1.31E-08	9.01E-09	2.27E-08	8.49E-05	8.50E-05	2.08E-05
37.50	8.50E-09	1.45E-09	1.21E-08	4.04E-04	1.10E-04	8.80E-05
43.75	2.75E-08	1.94E-08	2.47E-08	2.69E-04	3.77E-04	1.35E-05
50.00	3.91E-08	3.83E-08	6.62E-08	2.89E-04	6.05E-04	2.27E-04
-						
-						
-						
-						
-						
2956.25	1.17E-08	3.91E-09	6.15E-08	8.95E-04	1.33E-02	4.43E-04
2962.50	0.00E+00	5.51E-09	4.56E-08	2.03E-03	1.77E-02	8.28E-04
2968.75	1.27E-08	5.66E-09	4.81E-08	5.10E-04	5.50E-03	2.89E-04
2975.00	1.96E-08	4.28E-10	5.93E-08	3.36E-03	1.10E-02	9.40E-04
2981.25	4.36E-09	2.02E-09	1.78E-08	6.27E-04	2.51E-02	4.36E-04
2987.50	1.63E-08	5.28E-09	8.09E-08	2.58E-03	1.97E-02	1.07E-03
2993.75	2.04E-08	3.68E-09	3.25E-08	4.42E-04	1.75E-02	5.27E-04
3000.00	5.60E-09	1.45E-09	4.26E-08	4.11E-04	2.46E-02	7.37E-04

Table 6: Recommended data template for vibration

DAQ Ch	Axis	Sensor	SN	Sensitivity	Unit	Calibration
0	W1	PCB 352A24	LW423412	101	mV/g	1
1	L	PCB 352A24	LW423413	101.6	mV/g	1
2	W2	PCB 352A24	LW423414	99	mV/g	1
3	Z1	PCB 352A24	LW423415	100.2	mV/g	1
4	Z2	PCB 352A24	LW423416	100.7	mV/g	1
5	Z3	PCB 352A24	LW423417	102.9	mV/g	1
6	Mic1	GRAS 47BX	402577	1.75	mV/Pa	0.997
7	Mic2	GRAS 47BX	402582	1.34	mV/Pa	1.008

Table 7: Recommended Table Template to record sensor sensitivities

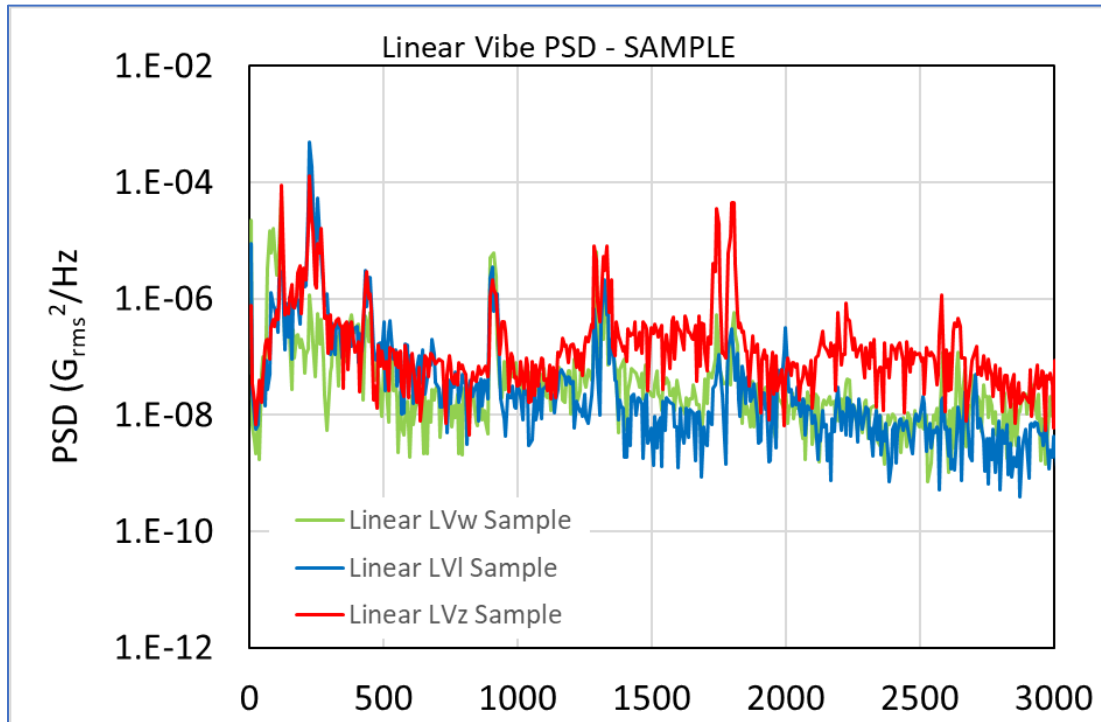


Figure 17: Recommended plot template for Linear Vibration (Frequency 0-3000Hz)

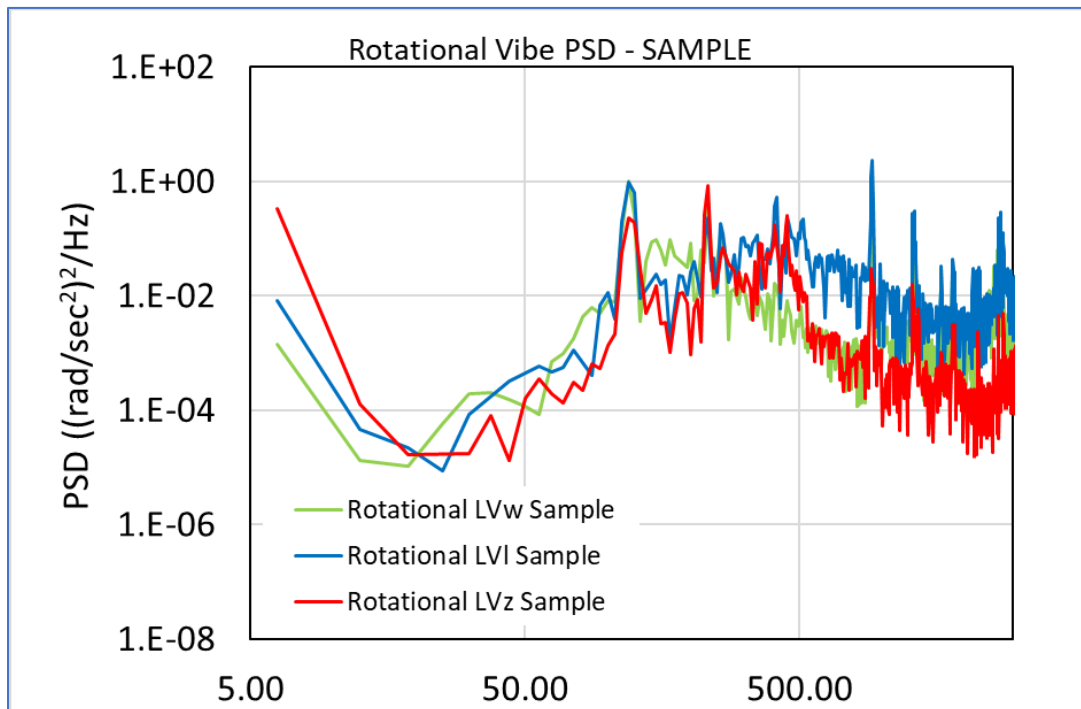


Figure 18: Recommended plot template for Rotational Vibration (Frequency 0-3000Hz)

7 Summary

The authors in conjunction with the OCP Storage Project Community have described hardware and communication tools to facilitate communication among companies on acoustical and vibration disturbances to HDD dynamics. CAD model of the surrogate and recommended sensors to be installed are provided in the design package. The HDD Dynamics Combined Acoustic & Vibration Surrogate resembles a simplified HDD, is made of Aluminum, and contains microphones and accelerometers at specific locations. Means for testing and acquiring signals relevant to the disturbances are detailed. Various learnings by participating members during voluntary validation of the manufacturing, assembly and testing using the combined surrogate are incorporated in this paper. Finally, a template and examples are provided for interchange of data among the users for assessment of HDD Dynamics risk.

Appendix A: Time Domain to Frequency Domain Considerations

A1 Background

During discussions within the sub workgroup looking at the variability of the HDD Dynamics Combined Acoustic & Vibration Surrogate, it became evident there were many ways to convert time domain data to the frequency domain. As a result, Appendix A was constructed to provide insight into particular analysis setting selections and when other settings may be selected due to different analysis requirements.

A survey revealed five different data acquisition systems and four different analysis systems to collect and reduce the surrogate time data. Given the small number of survey participants, it appeared that there would be ample opportunity to obtain different results based on the software choices for the different analysis systems available including those that develop their own code. Given the desire to communicate results between various users, a common time to frequency conversion would be preferred.

A2 Sine Wave Energy versus Amplitude

Understanding the difference between sine wave energy and amplitude is important when calculating acoustic and vibration surrogate data. The Siemens website has a page¹ describing the difference. The equivalent energy of a sine wave is equal to the RMS (Root Mean Square) value of the sine wave as shown in Figure 19 whereas the amplitude represents the peak value. The equation to calculate the RMS amplitude can be seen in equation 1.

¹ <https://community.sw.siemens.com/s/article/root-mean-square-rms-and-overall-level>

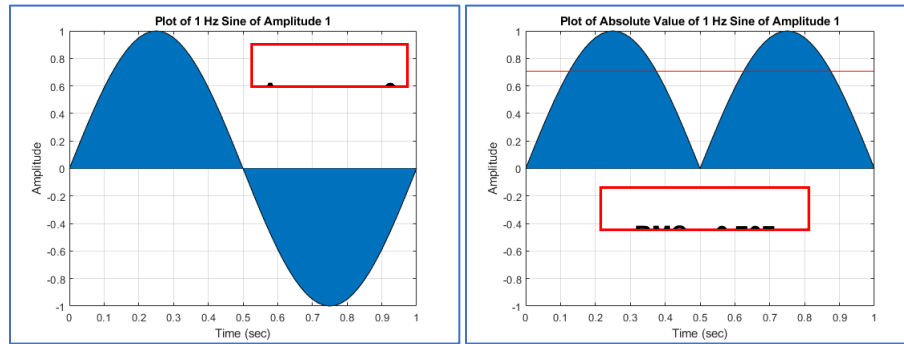


Figure 19: Sine wave RMS value

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^n A_i^2} = 0.707A \quad (1)$$

One concept that is important is Parseval's theorem² which states the total energy computed in the time domain must equal the total energy computed in the frequency domain (see Figure 20). This concept becomes important when applying a window function to a time domain signal. The analyst can choose between energy or amplitude correction. In general, energy correction should be used when evaluating surrogate results. This difference is explored in the further sections of this appendix.

$$\sum_{n=0}^{N-1} |X_n|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X(f_k)|^2$$

For:

$X_n \leftrightarrow X(f_k)$ is a discrete FFT pair and

N is the number of elements in the sequence

Figure 20: Parseval's theorem

² https://www.ni.com/docs/en-US/bundle/labwindows-cvi/page/advancedanalysisconcepts/lvac_parseval_s_theorem.html

A3 Conversion Strategies

There are at least three strategies to generate surrogate data.

A3.1 Commercial Software

The first is to use commercial software associated with the data acquisition hardware to collect time domain data and convert to power spectral density (PSD). In this case, the appropriate selection of computational parameters is important. The power spectrum (PS), linear spectrum (LS), and $1/3^{\text{rd}}$ octave data can be easily generated. The parameters listed in Table 4 are recommended for consistent data.

A3.2 Custom PSD Code

A second strategy is to use code to directly calculate the PSD data. Welch's Method to estimate the power spectral density utilizes window functions and overlapping segments to reduce noise in the power spectra. As an example, Matlab can be used to calculate the power spectral density directly using the pwelch function. The resulting unit for linear acceleration input is Grms^2/Hz and $(\text{rad}/\text{sec}^2)^2/\text{Hz}$ for rotational acceleration. A description of Welch's method can be seen on the Center for Computer Research in Music and Acoustics website³.

A3.3 Custom FFT/DFT Derived PSD

A third strategy is to use custom code to calculate the time to frequency domain conversion step by step starting with the basic discrete Fourier transform (DFT) or fast Fourier transform (FFT). In this case, a basic understanding of the computational methods to arrive at similar data results as the commercial software is important.

There are two concepts that were analyzed during the discussions: (1) how to adjust FFT magnitude due to the application of a window function and (2) how to average multiple segments.

³ https://ccrma.stanford.edu/~jos/sasp/Welch_s_Method.html

Using a window to minimize leakage and emphasize certain frequency domain characteristics is very common. In the time domain, each segment of a signal is multiplied by the window function which distorts both the amplitude and energy of the signal. Figure 21 shows multiple time domain segments after multiplication by various window functions. The window functions, from left to right, are the Uniform or Rectangular window, the Hann window, the Flattop window, and the Hamming window. The Uniform or Rectangular window multiplies the signal by 1 so there is no change to the signal magnitude or energy. One can see the magnitude difference for the remaining window types leading to reduced energy.

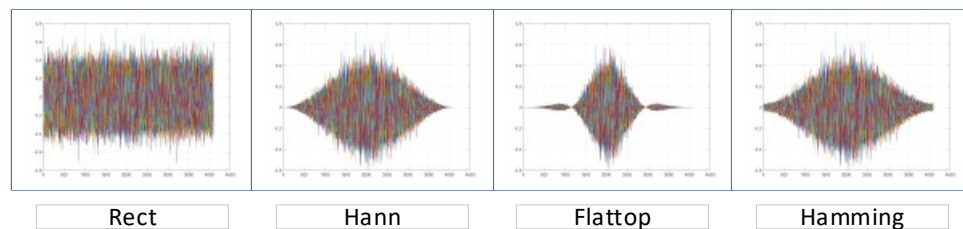


Figure 21: Time domain segments after multiplying by window

If the analyst is interested in the overall energy contained within the measurement, then energy correction is suggested for all except the Boxcar window. This is typical for acoustic measurements. If the analyst is interested in peak amplitude such as when calibrating an accelerometer to a known input, then amplitude correction is suggested.

A3.4 Energy versus Amplitude Correction

Much of the information contained in this section can be found in a series of web pages on the Siemens website⁴. The link points to the index of articles where specific topics can be found for both acoustics and digital signal processing. Of special interest for this section would be the following topics in the index:

1. “Windows and Leakage”
2. “Window Types”

⁴ <https://community.sw.siemens.com/s/article/Index-of-Testing-Knowledge-Articles>

3. “Window correction factors”

Once the FFT has been calculated, the results should be multiplied by the appropriate energy or amplitude correction factor shown in Table 8.

Table 8: Table of window correction factors

Window Type	Amplitude Correction	Energy Correction
Uniform	1.0	1.0
Hann	2.0	1.63
Flattop	4.18	2.26
Blackman	2.80	1.97
Hamming	1.85	1.59
Kaiser-Bessel	2.49	1.86

There is some debate on the Flattop and Blackman correction factors listed in Table 8. A web search led to a different set of correction factors for the Flattop and Blackman windows⁵ but equal for the remaining factors. Figure 22 lists one definition of the amplitude and energy correction factors which are also found in Matlab posts⁶. The resulting correction factors along with the Siemen’s factors can be seen in Table 9 with the non-equal correction factors highlighted in yellow.

$$\text{Amplitude Correction Factor} = \frac{1}{\text{mean}(w(n))}$$

$$\text{Energy Correction Factor} = \frac{1}{\text{rms}(w(n))}$$

Figure 22: Matlab post definition of amplitude and energy correction factors

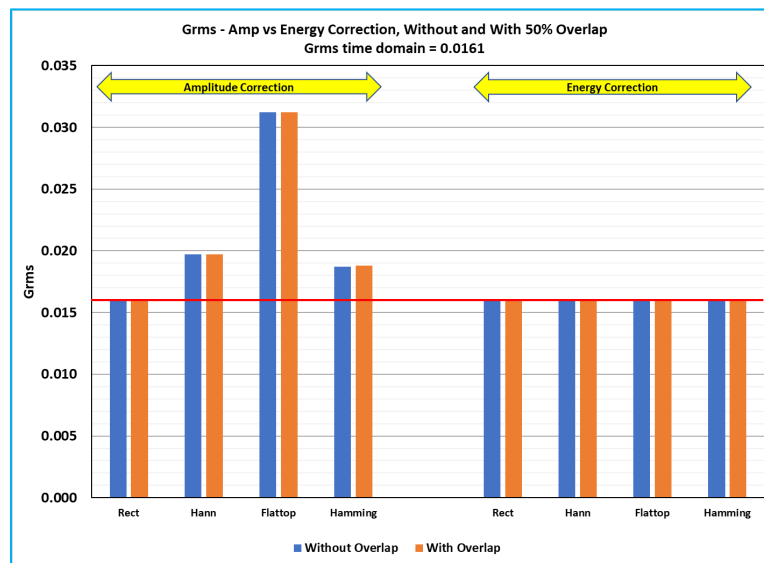
⁵ <https://dsp.stackexchange.com/questions/85277/what-is-the-energy-correction-or-amplitude-correction-for-a-tukey-window>

⁶ <https://www.mathworks.com/matlabcentral/answers/372516-calculate-windowing-correction-factor>

Table 9: Comparison of correction factors

	Seimens		Matlab	
	Amp	Energy	Amp	Energy
Uniform	1.00	1.00	1.00	1.00
Hann	2.00	1.63	2.00	1.63
Flat top	4.18	2.26	4.64	2.39
Hamming	1.85	1.59	1.85	1.59
Blackman-Harris	2.80	1.97	2.79	2.00
Blackman			2.38	1.73

Grms values for an actual surrogate measurement comparing amplitude versus energy correction in addition to the use of 50% overlap processing are shown in Figure 23. Note that amplitude correction does not guarantee similar results whereas energy correction results in identical values independent of the window function. Note the time domain based Grms value is the same as the energy corrected Grms values. This highlights the conservation of energy between the time domain and frequency domain. Figure 24 and Figure 25 show PSD plots used to calculate the Grms values shown in Figure 23.


Figure 23: Amplitude vs energy corrected Grms for surrogate measurement

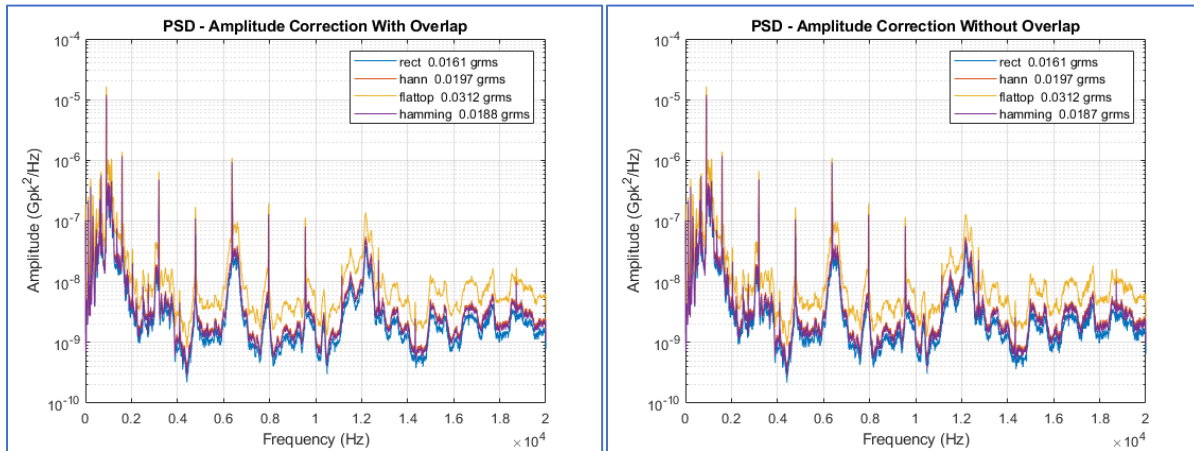


Figure 24: Amplitude corrected PSD plots

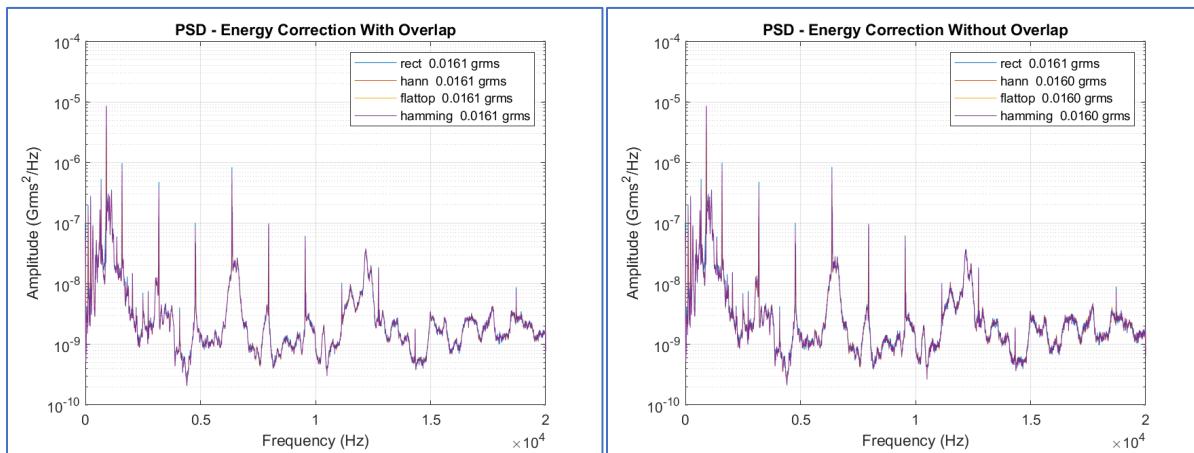


Figure 25: Energy corrected PSD plots

Figure 26 illustrates the effects of the different window functions when using energy correction.

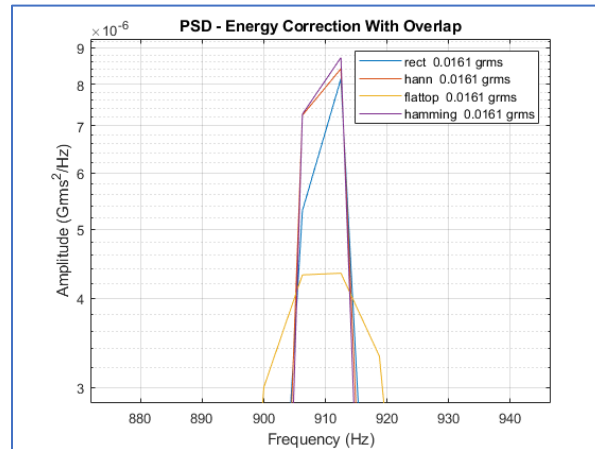


Figure 26: Energy corrected PSD zoom plot

A3.5 Averaging FFT Segments

Since long acquisition times will typically result in a number of shorter segments to convert to the frequency domain and especially with overlap processing, a method to average the resulting segments is required. The Siemen web site has a good description of FFT averaging of multiple segments⁷ in addition to the difference between spectrum and autopower functions⁸. Since surrogate measurements result in both acoustic and mechanical vibration data, the applicable window correction method should be energy correction. Averaging multiple records should use the energy average method.

To average multiple segments or blocks of frequency domain data, the average magnitude of the autopower linear spectrum is calculated as shown in Figure 27 which is the square root of the average power spectrum.

⁷ <https://community.sw.siemens.com/s/article/averaging-types-what-s-the-difference>

⁸ <https://community.sw.siemens.com/s/article/spectrum-versus-autopower>

$$\overline{FFT}(f_i) = \sqrt{\frac{1}{N} \sum_{i=1}^N FFT(f_i)^2}$$

For

$N = \text{number of segments}$

Figure 27: Definition of average auto linear spectrum

Appendix B: Vibration Calibration Methods

B1 Vibration Calibration

Because vibration data used in HDD Dynamics analysis are most often derived rather than direct measurements, i.e., combinations of multiple sensors, they cannot be contrasted to a known vibration calibration source. To assist with this gap, the workgroup has established a means to convey vibration calibration of the surrogate. The steps involved and expected results are described below.

Calibration can be performed to validate measurements on the individual surrogate level and account for discrepancies in surrogate materials, manufacture, and/or construction that would affect vibration calculations. This calibration allows a reasonable assumption that data collected at different locations using different surrogates can be comparable. The calibration process can be simplified as the below steps:

1. Measure accelerometer sensitivities and linear acceleration to derive correction factors, if necessary
2. Measure locations of the accelerometers to correct acceleration moment arms
3. Measure rotational acceleration to derive correction factors, if necessary
4. Measure weight to derive linear acceleration correction factors, if necessary

The accuracy of each step is determined by the available metrology and vibration test equipment. Table 10 illustrates various methods that can be used to calibrate the combined surrogate. It is recommended to use as many, and as precise of, the steps as possible. This document references the preferred PCB 352A24 accelerometer in all examples and steps.

Table 10: Calibration steps and methods

Calibration Step	Brief Description	Detailed Description
Linear Acceleration	Basic	Factory accel sensitivities
	Ongoing	Standalone calibrated accel sensitivities
	Shaker Based	Shaker derived accel sensitivities
Accelerometer Position	Nominal	Nominal moment arm distances
	Basic	Measured distances
	Precision	Precision distance measurements
Rotational Acceleration	Shaker Based	Rotational shaker derived correction factors
Weight	Precision	Weight differential from nominal

B1.1 Linear Acceleration Calibration

The purpose of this step is to calibrate the six individual accelerometers to a known standard and derive the necessary sensitivities and calibration factors to enter into the data acquisition software.

B1.1.1 Basic Linear Acceleration Calibration Method

Newly purchased accelerometers are shipped with factory calibrated sensitivity values, as depicted in Figure 28. The linear acceleration correction factor for each accelerometer using the basic method is simply the factory accelerometer sensitivity value.

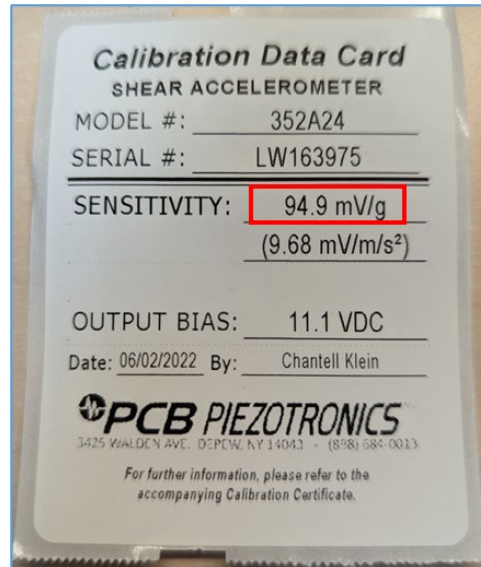


Figure 28: PCB accelerometer, factory-supplied calibration

B1.1.2 Ongoing Linear Acceleration Calibration Method

If accelerometers are calibrated on an ongoing basis, the new sensitivities should be used in place of the factory-supplied values, or included in the form of a calibration factor. Ongoing calibration can be performed with a standalone accelerometer calibrator. As an example, Figure 29 shows a PCB 394C06 hand-held shaker that is used for ongoing calibration. This shaker outputs a constant 1g peak acceleration at 159.2Hz.



Figure 29: PCB accelerometer calibrator

The linear acceleration correction factor (CF) from the ongoing method is the relation between the reference acceleration and the accelerometer measurement at the reference frequency. Equation 2 provides an example using the accelerometer Z1:

$$CF_{LV_{Z1}} = \text{Reference accel}_f / Z1_f \quad (2)$$

where CF is the correction factor, *Reference accel* is the measured reference acceleration in Gs, Z1 is the measured acceleration of Z1 in Gs, and the subscript denotes that values are to be taken at the reference source frequency, *f*.

This method requires the removal of each accelerometer from the surrogate, and their subsequent replacement. Care must be taken to install each accelerometer in the exact location from which it was removed.

B1.1.3 Shaker-based Linear Acceleration Calibration Method

If an electrodynamic or hydraulic shaker is available for use, the six accelerometers can be calibrated while installed in the surrogate. The calibration factors will be generated using the shaker control accelerometer as the acceleration reference.

This method requires mounting the surrogate to a shaker in such a way that the three principal directions (W, L, and Z) can be excited. This might mean using a three-axis shaker and a fixture that can align the surrogate in each axis, or a singular mounting fixture on three separate shakers. The surrogate mounting fixture should be designed so that there are no resonances in the 0-3000Hz range that would distort results. Figure 30 illustrates the surrogate mounted to one possible fixture and attached to a vertical (Z-axis) shaker table.

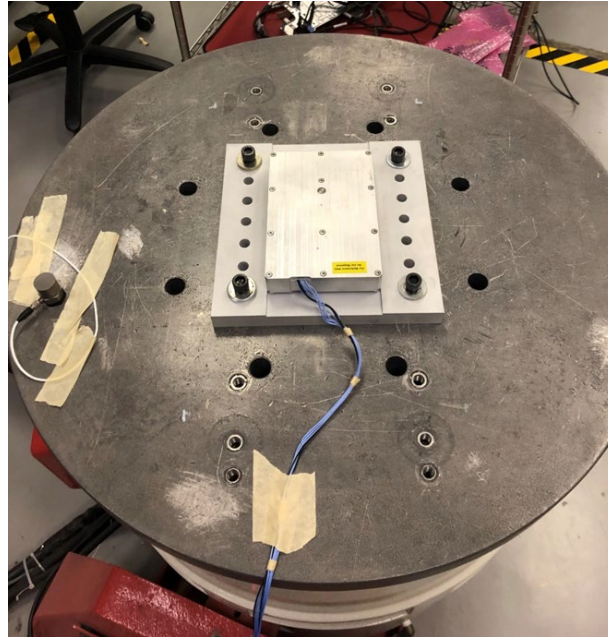


Figure 30: Example surrogate mounting fixture on single-axis shaker

With the surrogate-fixture assembly mounted to the shaker table, apply an input of either 1G peak 100Hz fixed sine or 1G peak swept sine from 5-500Hz in the desired axis. The correction factor for each individual accelerometer is then given by its relation to the shaker reference acceleration in its respective axis at 100Hz. Equation 3, below, exemplifies this process using accelerometer Z1.

$$CF_{LV_{Z1}} = \text{Shaker reference accel}_{Z100Hz} / Z1_{100Hz} \quad (3)$$

where CF is the correction factor, and *Shaker reference accel* and Z1 are acceleration values in Gs.

B1.2 Accelerometer Position Calibration

This step involves measuring the physical locations of the accelerometers and modifying the moment arms in the rotational acceleration calculations for R_W , R_L , and R_Z . To limit RV errors to

less than 1% for the shortest moment arm of 75 mm, measurement error should be ≤ 0.75 mm. Figure 31 illustrates the moment arm definitions and Table 11 contains the nominal moment arm measurements.

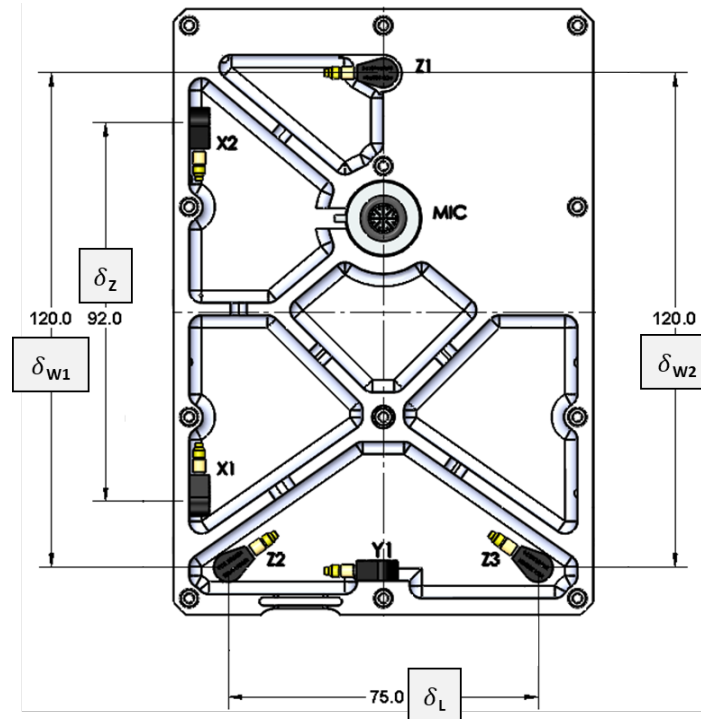


Figure 31: Surrogate moment arm definition and nominal measurements

B1.2.1 Nominal Accelerometer Position

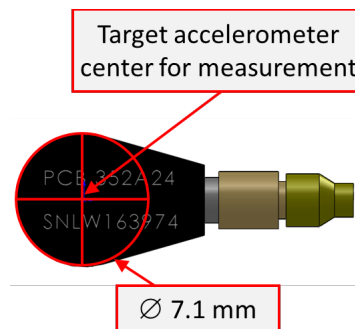
The nominal values for distances between accels are defined from the solid model. The nominal moment arm values are described in Table 11. These distance measurements are equivalent to the variables A, B, and C in Section 5.3.

Table 11: Nominal moment arm values

$A = \delta W1 = \delta W2$	0.120 m
$B = \delta L$	0.075 m
$C = \delta Z$	0.092 m

B1.2.2 Basic Accelerometer Position Measurement

Basic measurement describes measuring accelerometer physical positions using low precision methods, such as rulers or calipers. Measurements should be made from accelerometer center to accelerometer center for the four distances, as shown in Figure 32.


Figure 32: Accelerometer center position

B1.2.3 Precision Accelerometer Position Measurement

Precision measurement describes measuring accelerometer physical positions using high precision methods, such as optical comparators or coordinate measuring machines (CMMs). Measurements should be taken from accelerometer center to accelerometer center.

B1.2.4 Application of Measured Distances

The rotational acceleration equations should be modified to account for the actual distance measurements, as shown in Equations 4, 5, and 6:

$$R_W = 9.81 * (a_{Z1} - \frac{a_{Z2} + a_{Z3}}{2}) * (\frac{2}{\delta_{W1} + \delta_{W2}}) \quad (4)$$

$$R_L = 9.81 * (a_{Z2} - a_{Z3}) * (\frac{1}{\delta_L}) \quad (5)$$

$$R_Z = 9.81 * (a_{X1} - a_{X2}) * (\frac{1}{\delta_Z}) \quad (6)$$

where a are the accelerometer measurements in Gs, and δ are the moment arm measurements in m, collected from the accelerometer positional measurements.

B1.3 Rotational Acceleration Calibration

The goal of this step is to measure actual rotational acceleration response using a rotational shaker to:

1. Determine whether the methods from Linear Acceleration Calibration and Accelerometer Position Calibration resulted in rotational acceleration values within 5% of the reference source
2. Or, if the above steps were not used, directly derive the rotational correction factors

This method requires the use of rotational shakers. The surrogate should be mounted to the rotational shaker through a fixture that allows orientation for rotation about each axis.

Alternatively, multiple fixtures with different orientations can be used. Fixtures should not have any resonances between 0-3000Hz.

The shaker reference acceleration should be set for high signal to noise ratio, such as 20 rad/s² peak, and applied as either a 100Hz fixed sine or 5-500Hz swept sine. Correction factors should be determined at 100Hz for each output R_W , R_L , and R_Z by comparing measured rotational acceleration to the source. Equation 7 provides an example using R_W .

$$CF_{RW} = \text{Reference accel}_f / RW_f \quad (7)$$

B1.4 Weight Calibration

This step corrects for differences between the measured and nominal weight of the surrogate.

The weight correction factor is based on Newton's second law - that acceleration is force divided by mass. If the surrogate is heavier or lighter than the nominal weight, then the

measured acceleration will be either reduced or increased, respectively. The weight correction factor, CF_{weight} , for all accelerometers would then be calculated as follows:

$$CF_{weight} = weight_{nominal} / weight_{measured} \quad (8)$$

The weight correction factor from Equation 8 is then applied to all accelerometer measurements, as shown below:

$$\alpha_{i,weight\ corrected} = CF_{weight} * \alpha_{i,measured} \quad (9)$$

where α_i are the accelerometer measurements in Gs. The i subscript denotes that this correction is applied to each accelerometer on an individual basis.

The weight calibration method requires a calibrated precision scale. If possible, first check the scale calibration by measuring known accurate weights. Weigh the surrogate on the precision scale with the sensor wires suspended to minimize their contribution to weight. Figure 33 provides an example of this process. The nominal weight of the surrogate is 0.697kg.

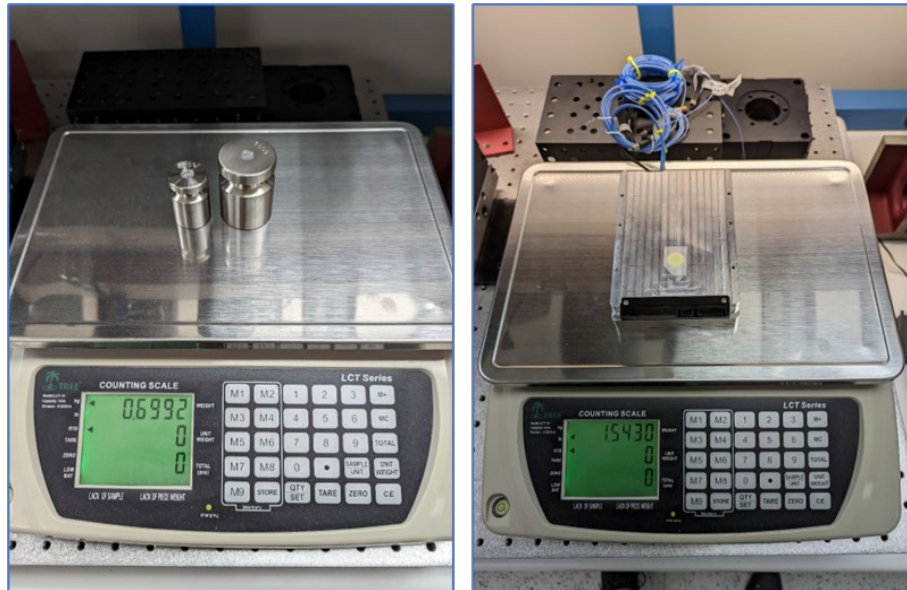


Figure 33: Scale calibration and surrogate measurement example

Appendix C: Variability Reduction

The variability reduction group generated a document listing the methods to assess measurement variation, results from the participating group members, and background discussion material. The group also developed an Excel template for logging the applicable measurement data.

Key slides from the document include Recording, Transformation, Processing, Details, and Test Log. The key parameters selected for variability measurement are listed in Table 12.

Table 12: Variability measurement parameter list

Parameter	DOFs	Units	Function	Window	Correction
Linear vibration, total area under the curve	L _w L _L L _z	Grms	PSD	Hann	Energy
Rotational vibration, total area under the curve	R _w R _L R _z	rad/sec ² rms	PSD	Hann	Energy
SPL, total area under the curve	P _u P _L	dB	PSD	Hann	Energy
Fan spin frequency linear vibration spectral amplitude	L _w L _L L _z	Gpk	sqrt(PS) or LS	Flattop	Amplitude
Fan spin frequency rotary vibration spectral amplitude	R _w R _L R _z	rad/sec ² peak	sqrt(PS) or LS	Flattop	Amplitude
Blade passing frequency SPL spectral amplitude	P _u P _L	dB	sqrt(PS) or LS	Flattop	Amplitude
1/3 Octave containing spin frequency linear vibration spectral amp	L _w L _L L _z	Grms	PSD	Energy	Energy
1/3 Octave containing spin frequency rotary vibration spectral amp	R _w R _L R _z	rad/sec ² rms	PSD	Energy	Energy
1/3 Octave containing blade passing frequency SPL	P _u P _L	dB	PSD	Energy	Energy

In order to determine variability, multiple measurements are required by removing and re-inserting the surrogate into the same chassis slot. Selected parameter means and standard deviations are calculated and the coefficient of variation (CV) calculated as defined by the ratio

of the standard deviation to the mean. The comparative magnitude of the CV then becomes the variability measurement.

The following graphs list CV results from the group illustrating the variability for the selected acoustical and acceleration parameters. These are listed to provide a point of reference for variation from existing OCP Combined surrogate users.

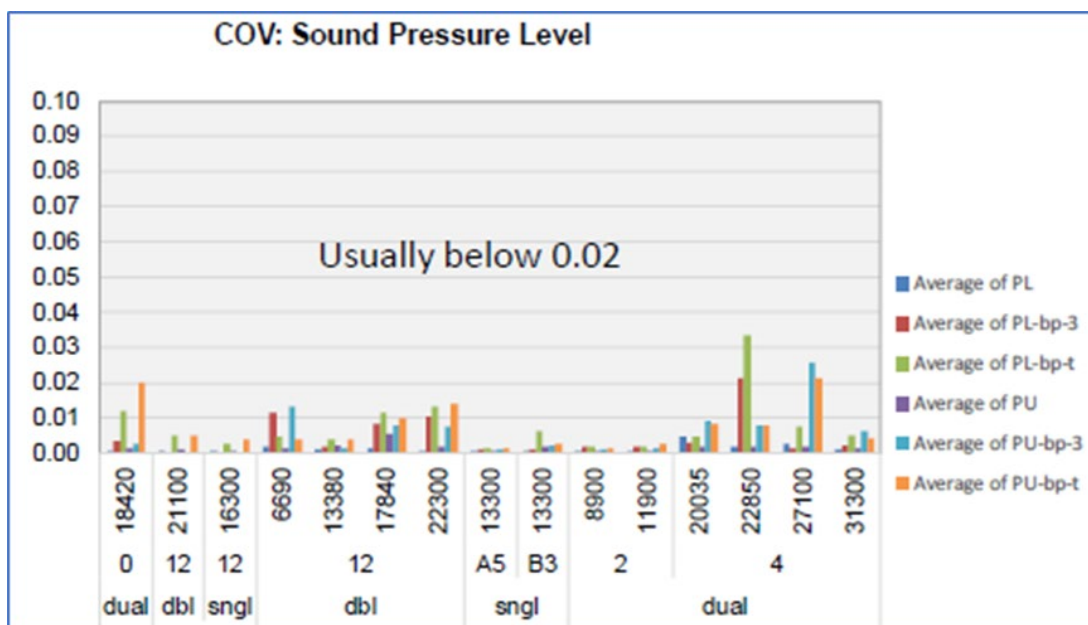


Figure 34: Sound pressure level CV results (slide 10)

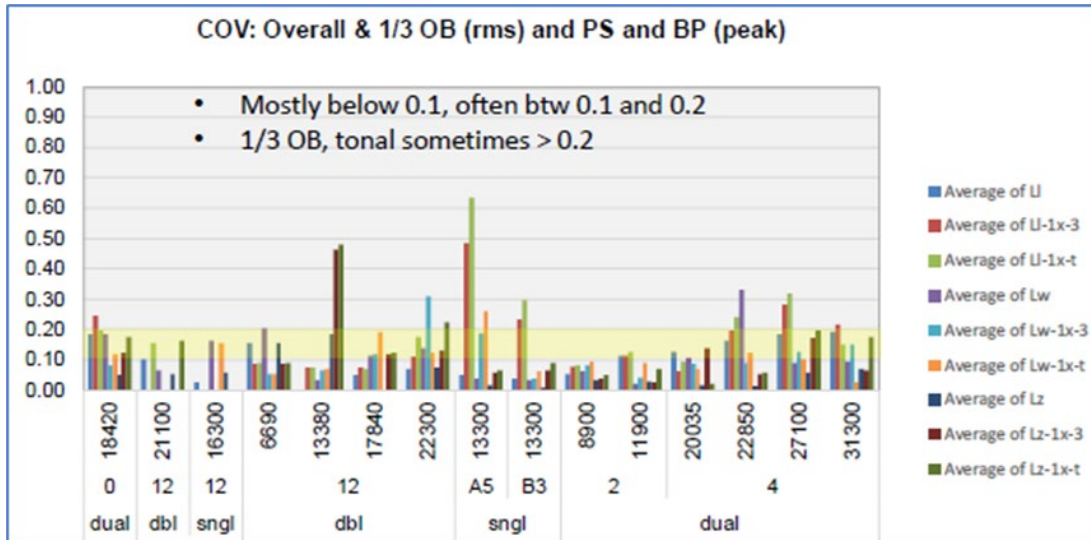


Figure 35: Linear vibration CV results (slide 12)

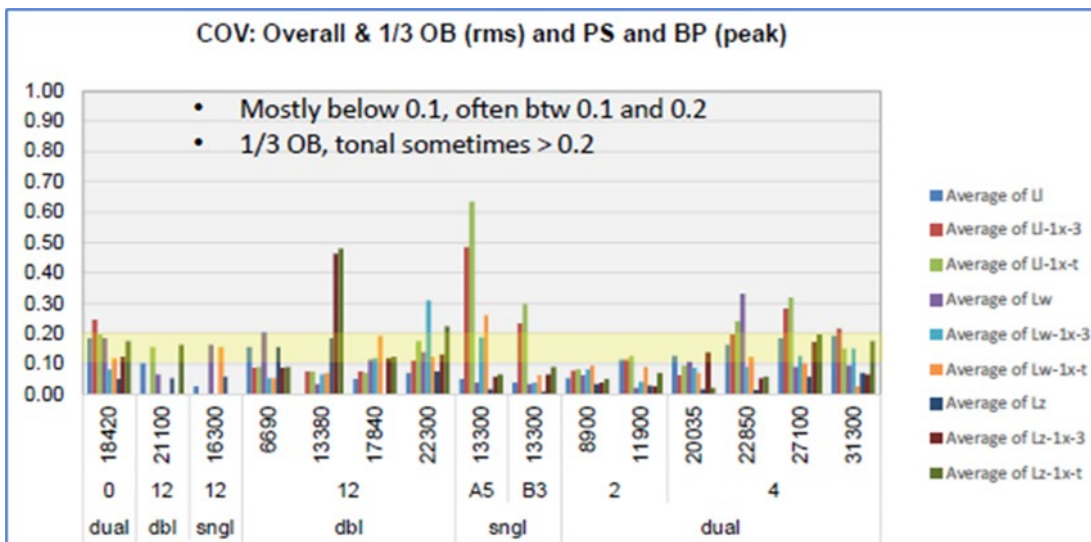


Figure 36: Rotary vibration CV results (slide 13)