101 Evergreen Drive
Bozeman, MT 59715
USA

February 21, 2024

4200-2-MK001_1.0

Cryostat 3-axis Vibration Testing: Questions to Ask a Cryostat Manufacturer About System Vibrations

Britt Pratt, David Dranchak, Tyler Vogel

Introduction

Cryostats used in environments containing optical and laser equipment must have vibrations mitigated to successfully conduct experiments. Understanding how a cryostat manufacturer mitigates vibrations in their systems as well as how they test for vibrations are two important criteria for potential customers to consider when selecting a cryostat for use in their experiments.

How are Vibrations Mitigated at the Sample Platform?

Vibrations on the sample platform can be mitigated by designing certain features into the cryostat. These features can limit the vibrations from different sources (external or internal), shift the vibrations away from the sample platform to somewhere else in the system, or both. The largest contributor of vibrations is the operation of the cryocooler, so the design must mechanically decouple the cryocooler from the sample space to reduce system vibrations to an acceptable level. The challenge with mechanically decoupling the system is to provide adequate vibration isolation while still maintaining optimal thermal conductivity to cool the sample as well as having optical access to the sample.

It is important to mechanically decouple the system from the outside environment as much as possible, as these vibrations are much more difficult to identify and more difficult to mitigate with designed damping alone. The most common form of mechanical decoupling is to decouple the system from the floor and surrounding environment by having the system mounted on a floating optical table or on springs. This can reduce the effects of vibrations on the system that are caused by outside phenomena.[4]

Vibrations from the operation of the helium compressor are more difficult to reduce but can be damped by maximizing surface contact of connected hoses on the floor, as opposed to suspended in the air—connecting the compressor to the cryostat system. Passing the hoses through a denser substrate such as sand can also help reduce vibrations.[5] An example of these external damping features can be seen in Figure 1.

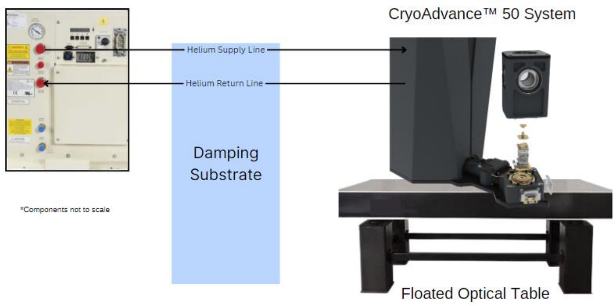

Figure 1: Example of internal and external damping within a cryostat system.

Due to the units at which vibrations are measured in a cryostat system (nm), minor and miniscule details can drastically increase vibrations in the system. Loose screws and other hardware can easily increase vibrations in the system by 3 times.[1]

To align sensitive optical experiments the use of a nanopositioner in the sample space of optical cryostats is common. Nanopositioners in a sample space can increase vibrations at the sample mount, as the ceramics used in their construction do not damp vibrations well due to high transmissibility, an effect that also increases as temperature decreases.[2,3] Geometry and materials used in both nanopositioners and other types of sample mounts are important characteristics to consider when choosing a sample mounting method, as they can have a significant effect on experienced vibrations at the sample.

Another consideration regarding sample supports and mounts is how their use can affect measured vibrations. As the sample supports increase in height, there is a

tel: +1.406.551.2796 | fax: +1.406.551.2797
info@montanainstruments.com | www.montanainstruments.com

greater chance to see an increase in vibrations at the top of the support (where the sample would be mounted). The use of screws to secure the support to the platform can also cause an increase in vibrations compared to other securing methods such as welding. While the increases can be miniscule, it is still important to again consider the material and geometry of the support and mount, as well as the securing method used for the support, to mitigate translated vibrations as much as possible.

By designing vibration damping features into the cryostat, more sensitive optical and laser equipment can be used with the system. The use of external damping features such as an optical table and a damping substrate for compressor hoses further decreases experienced system vibrations. This allows for more complex experimental setups and more advanced research to be conducted. To test the dampening effects of the system design as well as overall system quality, the cryostat manufacturer should test the system for vibrations using one of the methods discussed in the next section.

What is the Difference Between Single-Axis and 3-Axis Vibration Testing and Which one should you do?

3-axis testing involves testing all three axes (x, y, and z directions) independently for translated vibrations.[4] Single-axis testing involves only testing in one direction, which can be misleading depending on which direction is chosen and subsequently used for the published specification. For example, if the z (vertical) axis is chosen for a single-axis test, the measured vibrations are likely much lower than the other two axes. This is due to there being less translated vibrations in the z direction in most standard cryostat operating setups.[4]

A good visualization of why the z direction has less translated vibrations is a stone thrown into a body of water. Even though the stone hits the water in a mostly vertical direction, the main waves seen at the point of impact are propagated on the surface of the water, not vertically into the water (the stone's direction of travel). With that in mind, knowing which type of test a cryostat manufacturer uses for vibrations can help a potential customer better interpret published vibration specifications. In addition to the type of test conducted, the testing equipment used can also affect the measured vibrations.

What Testing Equipment Do You Use?

The most common ways to measure vibrations is a capacitive sensor or laser interferometer. Using a capacitive sensor like the one shown in Figure 2 to test for vibrations can provide accurate results with relative minimal setup compared to other testing types. Capacitive testing is also less expensive than other testing options.

Laser interferometer tests are more accurate than using capacitive sensors and can be used to test vibrations in more complex systems. Capacitive sensors can be susceptible to increased interference from other sources (noisy power supply, electrical noise from light fixtures, etc.), depending on sensitivity of the sensor and how well the noise sources are mitigated within the testing environment.

Laser interferometry is more expensive and complicated to setup compared to capacitive sensor testing. These laser setups are also much more sensitive to outside acoustic and electrical noise than capacitive sensors, requiring increased mitigation of these sources or shielding of the testing setup from the sources of noise to perform an accurate test.

The equipment being used also determines what type of testing can be completed. Capacitive sensors can accomplish both single and 3-axis testing but often require more robust fixturing to accurately conduct 3-axis tests compared to single-axis tests. Capacitive testing also produces more accurate results when mounted on an optical table along with the system being tested, which means that limited or no access to an optical table could hinder testing or produce inadequate and inaccurate test results.

Laser interferometer testing can accomplish both single and 3-axis testing, although at a significantly higher cost and a higher degree of difficulty in setup and operation than a capacitive sensor. The sensitivity of a laser interferometer setup also limits its use in high noise and vibration environments.

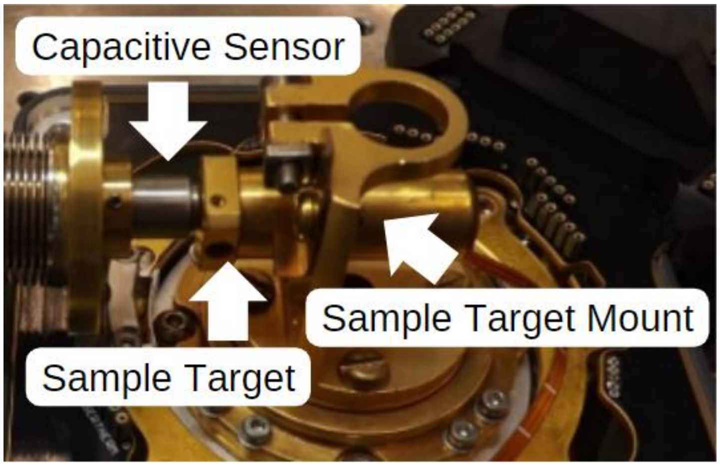

Figure 2: Single axis capacitive sensor vibration test setup on 50mm sample chamber.

The combination of testing equipment and type of test can drastically affect the measured vibrations in a cryostat system. Potential customers can ask about both the testing equipment used, and the type of vibration test conducted to better understand a manufacturer's listed vibration specification.

What is the bandwidth for Measured Vibrations?

The frequency range of vibrations are just as important as the displacement values of a measured vibrational wave. It is important to know the frequency range of the measurement to obtain information about which frequencies have the most energy. It is also imperative to avoid resonant frequencies of materials used within the system. If parts of the system vibrate at their respective resonant frequency, the overall system vibrations can be too excessive to complete an experiment or obtain any meaningful data. In optical setups, for example, resonant frequencies can cause mirrors and precisely aimed lasers and optics to shake, rendering the setup and current experiment useless. Figures 3a and 3b illustrate the difference in displacement of vibrations measured with different high pass filters.

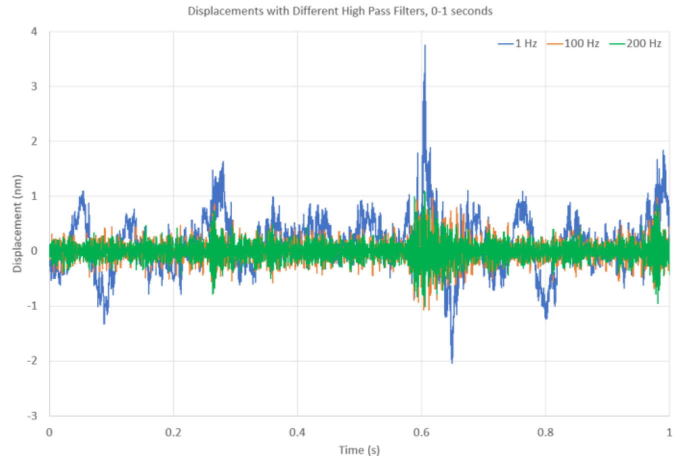

Figure 3a: Measured vibrations with 1 Hz, 100 Hz, and 200 Hz high pass filters, 0-1 seconds.

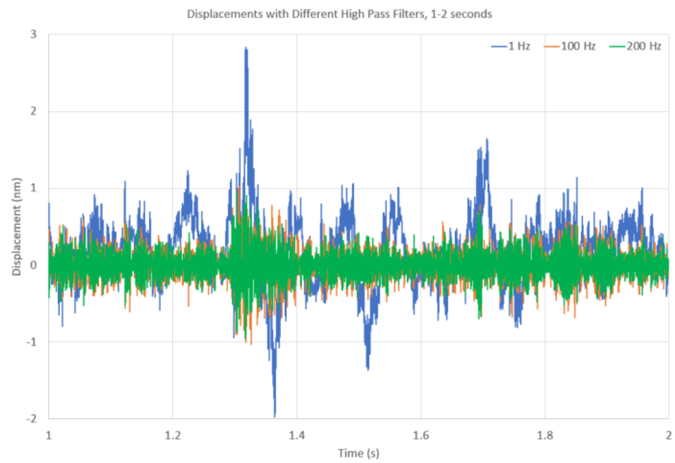

Figure 3b: Measured vibrations with 1 Hz, 100 Hz, and 200 Hz high pass filters, 1-2 seconds.

High-Level Solution

Interpreting a cryostat's vibrational performance from a manufacturer can sometimes be difficult, as the manufacturer's listed specification might not be telling the full story. Some only test in one axis direction instead of in three, which can mean the vibrations experienced are higher than what is listed on their specification sheet. By asking the following questions seen in Table 1, customers can be sure that the cryostat system has been tested to the highest standard and that it will meet the vibration requirements they need.

Questions to Ask Manufacturer	Customer Insights from Question
How are vibrations mitigated at the sample platform?	Tells a customer how much vibrational damping is engineered into the system such as: damping features (springs, rubber dampers, bellows, etc.), acoustic decoupling, mechanical decoupling, or ideally a combination of the three.
What is the difference between single-axis and 3-axis vibration testing, and which do you do?	Tells a customer how close to a real-world use case the manufacturer's measured system vibrations are depending on the type of test ran.
What testing equipment do you use?	Tells a customer if the testing equipment used produced the most accurate results in a timely fashion.
What is the frequency bandwidth of the measured vibrations?	Informs the customer about which frequencies have the most vibrations/energy.

Table 1: Questions to ask cryostat manufacturer and customer insights gained from questions asked.

All Montana Instruments cryostats undergo vibration testing prior to shipping. Table 2 lists the vibration specifications for the full Montana Instruments cryostat product line.

Product	Vibration Specification, peak-to-peak*
CryoAdvance™ 50	<5nm
CryoAdvance™ 100	<15nm
Cryostation® s200	<15nm (x/y direction only)

*Base system specification. Accessories and other installed options may affect these values. All 3 directions tested unless otherwise noted. All systems test at or better than specification. Optical table used as reference point for vibration measurements.

Table 2: Vibration Specifications for Montana Instruments Cryostats.

Montana Instruments Test Procedure

To test vibrations, the fixture shown in Figure 4 is used. A capacitive sensor is inserted into the thru holes in the fixture to test.

Figure 4: Example vibration test fixture.

The sensor is connected to a capacitive controller that outputs to an oscilloscope and compatible software for data acquisition. The fixture is mounted securely to the sample chamber and an optical table. A capacitive sample target is mounted in the sample chamber so that the sensor can measure the vibrations of the target, which simulates what a real sample mounted in the chamber would experience during system operation.

The sensor has an optimal placement distance from the sample target that is indicated on the drive electronics by a green or red light. A ground wire from the controller is also connected to the optical table. Measurements are recorded at ambient conditions with the vacuum housing and radiation shield removed for more convenient access to the mounted target. Measurements are taken over a 2 second period. The Cryostation® cold head and compressor are also turned on for approximately 30 seconds to simulate real use case vibrations that would be experienced when the cold head and compressor are operating.

The following equipment is used to conduct the vibration test:

Lion Precision drive electronics CPL-190 (resolution at 1 kHz .3-.5 nm RMS, 3-5 nm peak-to-peak) and a Lion Precision (C8-3.2) capacitive probe with 3.2mm sensing area diameter (fine 50µm range, resolution of 0.25nm)[9] are used in conjuncture with the test fixture and sample mount sensor target. Using this equipment allows for vibration measurements up to a hundredth of a nanometer (10 picometers). [9]

A PicoScope 4224 Oscilloscope with a 1 Hz high pass filter and PicoScope Software are used for data collection and exporting.

The optical table is the point of reference for the vibration test. The resonant frequencies of the table affect the frequency of the low pass filter that is used during testing. With resonant frequencies of the table at different points in the natural frequency range between 30-600 HZ, filters are chosen to attenuate unwanted frequencies and pass through target frequencies, and result in improved test results.

The equipment used can be seen in further detail in Figure 5.

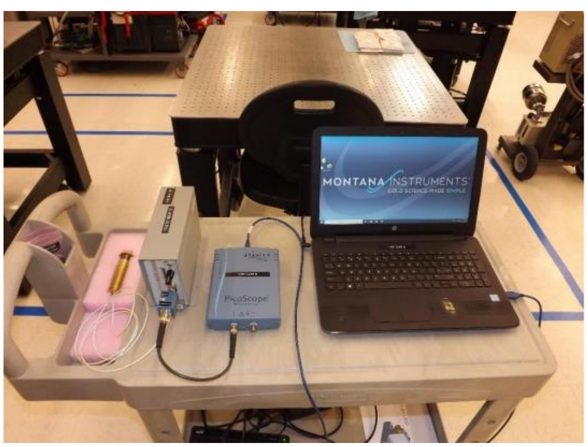

Figure 5: Vibration testing equipment.

Analysis Procedure

Vibration measurements taken using a capacitive sensor can be measured as a displacement value.[5,6] Displacement, d, is calculated given the following:

$$d = \frac{Output\ Change}{Sensitivity}$$

Vibration displacement measurements using capacitive probes are based on the following relationship:

$$C \propto \frac{1}{d}$$

A measured change in capacitance, C, is proportional to a change in distance from the capacitive probe to the sample target (displacement).[7] Therefore, any change in capacitance is a result of the displacement between the probe and the target. In this case the displacement is being caused by vibrations felt within the system. Vibration measurements can be peak-to-peak (p-p) or root mean square (RMS) displacement values. P-P is the maximum amplitude (in this case representing displacement) measured in each time interval, while RMS is a derived amplitude representing the average amplitude of the signal. RMS vibration measurements are lower than p-p values as they are more resistant to outliers and generally a more accurate representation of experienced vibrations. P-P values are a more conservative representation of experienced vibrations as they are maximum measured values.[5,8,10] Figure 6 is a graphical representation of the above description of p-p versus RMS values.

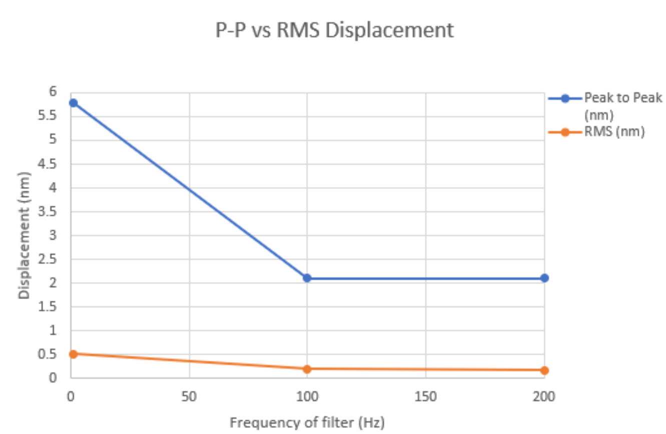

Figure 6: Peak-to-peak versus RMS displacement measurements over range of frequency filters.

While displacement is the parameter used from the vibrational data, it is not the only parameter that can be derived from the time trace vibration data. Velocity, usually in millimeters per second, and acceleration, usually measured in g's, can also be derived from the amplitude of displacement (or by taking the first and second derivative of displacement, respectively). As previously discussed, frequency can also be obtained from vibrational data. Depending on the measurement device and software, phase (the relative timing of the vibration waveform measured in degrees) can also be obtained.

Conclusion

When reviewing a cryostat manufacturer's vibration specification, it is important to understand how the system was designed to minimize vibrations and how the manufacturer tests and measures system vibrations. All Montana Instruments cryostats go through rigorous vibrations testing prior to shipment to ensure the system will meet or exceed design specifications.

References

1. 6 Common Causes of Machine Vibrations, istec.com, ISTEC, last modified 15 June 2022, https://www.istec.com/en/6-common-causes-of-machine-vibrations/
2. Rice, Brian, Quinzi, Joseph, Lund, Lance, et al. "Method to Measure Young's Modulus and Damping of Fibers at Cryogenic Temperatures" | University of Rochester (2014).
3. 8 Environmental Factors Affecting Vibration Measurement Accuracy, machinedesign.com, Machine Design, last modified 30 August 2018, https://www.machinedesign.com/mechanical-motion-systems/press-release/21837096/8-environmental-factors-affecting-vibration-measurement-accuracy
4. Micke, P., Stark, J., King, S. A., et. al. "Closed Cycle, Low-Vibration 4 K Cryostat for Ion Traps and Other Applications" | Max Planck Institute for Nuclear Physics (2019).
5. Vibration Measurement; Vibration Sensors; Measuring Vibration Precisely, lionprecision.com, Lion Precision, last modified 19 April 2019, https://www.lionprecision.com/vibration-measurement-and-sensors/
6. Linear Position and Displacement Measurement With Capacitive and Eddy-Current Sensors, lionprecision.com, Lion Precision, last modified 19 April 2019, https://www.lionprecision.com/linear-position-and-displacement-measurement-with-capacitive-and-eddy-current-sensors/
7. Capacitive Sensor Operation and Optimization, lionprecision.com, Lion Precision, last modified 2 December 2015, https://web.archive.org/web/20151202093819/http:/www.lionprecision.com/tech-library/technotes/cap-0020-sensor-theory.html
8. Vibration- The Most Common Amplitude Units in Use, updateinternational.com, Update International, https://updateinternational.com/Book/VibrationBook1d.htm
9. Capacitive Sensor Brochure, Lion Precision, https://www.lionprecision.com/wp-content/uploads/2022/07/Brochure-Capacitive-Probes.pdf
10. The Peak, Peak to Peak and RMS Values in Vibration Analysis, dynamox.com, Dynamox, https://dynamox.net/en/blog/the-peak-peak-to-peak-and-rms-values-in-vibration-analysis