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Acousto-Optic Laboratory

Vibration Survey of Room 47 with a Laser Doppler Vibrometer

Main Laboratory Basement, U.S. Army ERDC-CRREL

Carl R. Hart

November 2020

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Abstract

Plans are underway to create an acousto-optic laboratory on the campus of the Cold Regions Research and Engineering Laboratory. For this purpose, existing space in the basement of the Main Laboratory will be renovated. Demanding measurement techniques, such as interferometry, require a sufficiently quiet vibration environment (i.e., low vibration levels). As such, characterization of existing vibration conditions is necessary to determine vibration isolation requirements so that highly sensitive measurement activities are feasible. To this end, existing vibro-acoustic conditions were briefly surveyed in Room 47, a part of the future laboratory. The survey measured ambient noise and ambient vertical floor vibrations. The ambient vibration environment was characterized according to generic velocity criteria (VC), which are one-third octave band vibration limits. At the time of the survey, the ambient vibration environment fell under a VC-A designation, where the tolerance limit is 2000 μin/s across all one-third octave bands. Under this condition, highly sensitive measurement activities are feasible on a vibration-isolated working surface. The conclusion of this report provides isolation efficiency requirements that satisfy VC-E limits (125 μin/s), which are necessary for interferometric measurements.

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Preface

This study was conducted for the Engineer Research and Development Center (ERDC) Programs Office under Program Element 611102, Project AB2, Task 01 (a 2363/FIF/DoD FLEX-4 program), "Acousto-Optic Laboratory." The technical monitor was Mr. William Ryder, ERDC Programs Office.

The work was performed by the Signature Physics Branch of the Research and Engineering Division, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Dr. M. Andrew Niccolai was Branch Chief; and Mr. J. D. Horne was Division Chief. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

Appreciation goes to Mr. Ken McKay, technical point of contact for the Technical Manufacturing Corporation, for insightful discussions regarding vibration isolation. Discussions with Mr. Terry Harwood, Mr. Edward Coleman, and Mr. Andrew Bernier (ERDC-CRREL) lead to an important connection between the campus 56-ton chiller and observed vibrations.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
inches	0.0254	meters
microinches	0.0254	micrometers

1 Introduction

1.1 Background

On the campus of the U.S. Army Engineer Research Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), plans are underway to renovate a space for an acousto-optic laboratory. Central to this laboratory will be two optical table systems. These will serve as a working surface and vibration isolation system for acousto-optic experiments. Since highly sensitive measurements require very low ambient levels of vibration, it is necessary to characterize the ambient vibration environment so that a vibration isolation system may be specified.

1.2 Objectives

To inform the creation of vibration isolation requirements so that highly sensitive measurement activities are feasible, this study conducted a vibration survey in Room 47 of the Main Laboratory Basement. The objective was to collect and analyze ambient acoustical and vertical floor vibrational data.

1.3 Approach

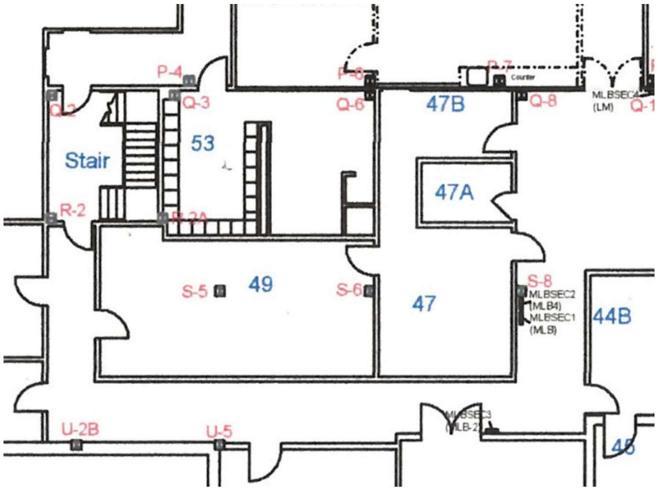
To accomplish this, measurements were collected with a condenser microphone and a laser Doppler vibrometer (LDV). An LDV is a stand-off measurement technique with a sufficiently wide bandwidth to measure low-frequency vibrations. Although direct-contact measurements are preferable, due to fewer sources of experimental error, accelerometers that were available did not have sufficient bandwidth to measure low-frequency vibrations.

Ambient acoustical and vertical floor vibrational data were analyzed to quantify the ambient vibro-acoustic environment. Digital signal processing of time-series data, to one-third octave band levels, provided summary metrics that characterized the ambient environment of the survey site.

2 Experimental Methods

The survey site was Room 47 of the Main Laboratory Basement. Figure 1 shows this room adjacent to Rooms 47A, 47B, and 49, which will be combined into a single space for a future acousto-optic laboratory. Since Room 47A was inaccessible, it was eliminated from consideration. Rooms 47B and 49 are both carpeted, ruling out the possibility of directly measuring vibrations of the slab on grade. Room 47 contained rubber flooring laid over the concrete slab on grade. Since the flooring was not adhered to the subsurface, a portion was pulled back for direct measurement access. A portion of the slab on grade was exposed near the north door to Room 47.

Figure 1. Partial floor plan of the Main Laboratory Basement. North is to the *right* in the floor plan.



The major components of the measurement system consisted of a seismological digitizer, LDV, and condenser microphone. Table 1 enumerates all of the instrumentation used, along with channel assignments. The seismological recorder continuously digitized analog signals with 24-bit resolution at a sampling frequency of 2000 samples per second. A digital finite impulse response filter serves as an antialiasing filter, with a cutoff at 80% of the Nyquist frequency. The voltage range of this digitizer is 40 V* peak to peak (i.e., ±20 V), and a software selected gain of two reduced the voltage range to ±10 V. This voltage range matches the output voltage range of the LDV. The LDV measures vibrational velocity over a bandwidth of 0.5 Hz to

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* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *U.S. Government Publishing Office Style Manual*, 31st ed. (Washington, DC: U.S Government Publishing Office, 2016), 248–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

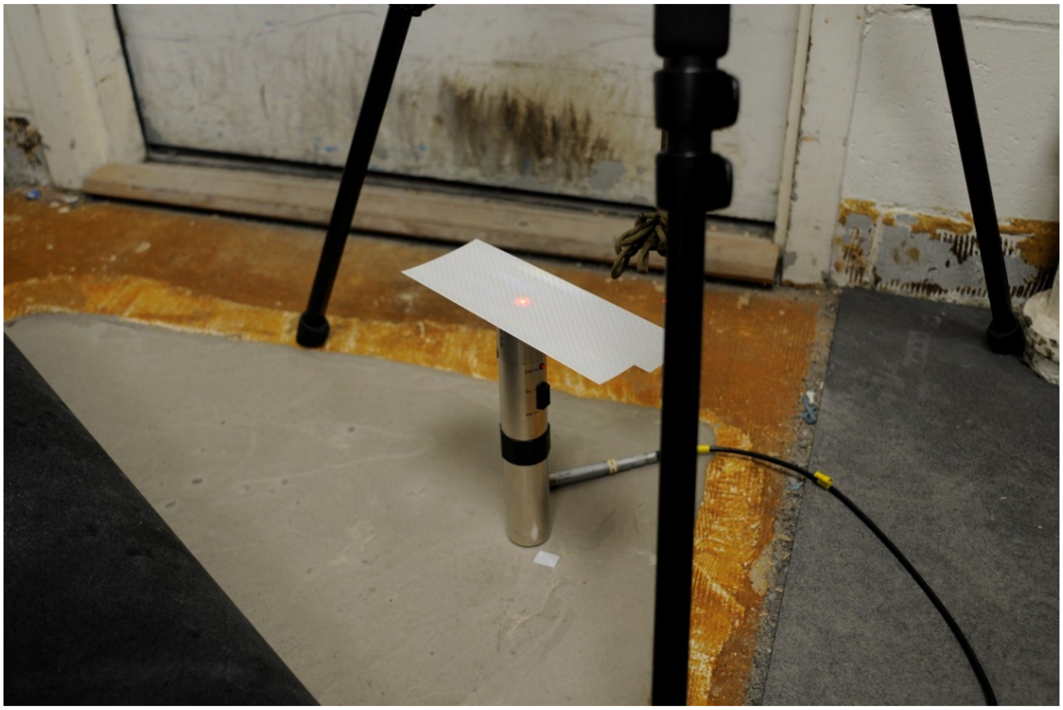
3 MHz (depending on measurement range). A measurement range of 10 mm/s/V was selected on the velocity decoder since it was the most sensitive setting available. A half-inch-diameter condenser microphone was paired with a microphone preamplifier. A microphone power supply at 200 V provided external polarization of the condenser microphone.

Table 1. Experimental instrumentation, equipment, and channel assignments.

Make	Model	S/N	Instrument/Equipment	Channel	
				Recorder	Oscilloscope
Geotech Instruments	SMART-24R	1266	Seismological recorder		
Tektronix	TDS3054	B016186	Oscilloscope		
Polytec	NLV-2500	0250229	Laser Doppler vibrometer	1	1
Brüel & Kjær	Type 4165	2068951	Condenser microphone (1/2 in. dia.)	2	2
Brüel & Kjær	Type 2669	2083444	Microphone preamplifier		
Brüel & Kjær	Type 2829	3169173	Microphone power supply		
Brüel & Kjær	Type 4228	3140004	Pistonphone (nominal 124 dB at 250 Hz)		
Odyssey	34M-PC1500		Battery (12 V, 68 Ah)		
Bushnell	Advanced Tripod		Tripod		

Calibrated analog signals, from both the LDV and microphone, were transmitted to both the seismological recorder and oscilloscope. Oscilloscope readings verified signal transmission and signal values, serving as a check against preliminary postprocessing of seismological recorder data. A pistonphone was used to input a calibrated signal into the microphone channel. Oscilloscope readings showed a root-mean-square (RMS) voltage of 1.47 V and a measurement frequency of approximately 251 Hz, which are well within the expected values for the pistonphone and microphone. Preliminary postprocessing of the recorder data indicated an RMS voltage of 1.47 V, as expected. The pistonphone was also used to check operation of the LDV. Figure 2 shows the pistonphone oriented vertically. A sheet of retroreflective tape, placed over the pistonphone opening, acted as a baffled surface. This arrangement verified that the LDV measured a 250 Hz signal. The LDV measured a range of 400 to 600 mV, RMS voltage. Variation in RMS voltage was due to not reproducing the exact placement of retroreflective sheet over the vertically standing pistonphone.

Figure 2. Vertically oriented pistonphone with retroreflective sheet acting as a baffle.



Ambient vertical floor vibrations and acoustic pressure were measured in front of the north door of Room 47. A plumb bob was placed next to the LDV head to approximately point the laser beam vertically downwards, as shown in Figure 3. In retrospect, capping the objective (lens) and placing the plumb bob below the center of the cap is a better positioning technique for marking the target point on the floor. At the laser target point, a piece of retroreflective tape was adhered to the concrete floor. The retroreflective tape is necessary to maintain the highest signal-to-noise ratio for the LDV system. The objective of the LDV head was adjusted to focus the spot size as best as possible. The sensor head was positioned at a stand-off distance of 43.75 in. above the floor. This distance corresponds to a visibility maximum, which is associated with a dual-mode state of the LDV's helium-neon laser. Halfway between visibility maxima are visibility minima, which can lead to severe degradation in the received signal (Polytec GmbH 2007, 4–8, 4–9). Nearby, the half-inch condenser microphone/preamplifier was placed on the floor.

Figure 3. LDV sensor head mounted on the tripod and the microphone placed on floor.

Table 2 provides the experimental sequence of events. At the start of acquisition, the seismological recorder was powered on, and a pistonphone was preplaced vertically with a sheet of retroreflective tape on top. The RMS voltage on the oscilloscope, for the LDV signal, was approximately 522 mV. Approximately 3 minutes later, the pistonphone was attached to the microphone. The oscilloscope reading was approximately 1.46 V RMS for the microphone signal and approximately 40 mV RMS for the LDV signal (noise). Approximately 3 minutes later, the pistonphone was removed from the microphone. About 12 minutes after the start of signal acquisition, the space was vacated for an extended duration. Room 47 was revisited 3 hours, 35 minutes later. The same procedure after startup was followed, and digital photographs were taken of the experimental setup. The seismological recorder was shut down 16 minutes after reentry.

Table 2. Experimental sequence of events on 28 June 2020. The time is as shown on the recorder. Local time was approximately 4 hours, 6 minutes behind.

Time (Recorder)	Event	Notes
00:29	Turn on recorder, begin acquisition	Small fan operating in room
	Baffle vertical pistonphone	522 mV RMS, LDV
00:32	Place pistonphone on microphone	1.46 V RMS, microphone
		40 mV RMS, LDV
00:35	Remove pistonphone from microphone	
00:36	Read recorder status	12.557 V in, 26.96°C, 86% free on D: (hot-swappable drive)
00:39	Leave	
00:40:30	Return	
00:41:30	Leave	
04:04:40	Return, take pictures	86% free on D:
04:12	Baffle vertical pistonphone	550 mV RMS, LDV
04:15:30	Place pistonphone on microphone	1.46 V RMS, microphone
04:20	Remove pistonphone from microphone	
04:20:30	Turn off recorder	

3 Vibration and Acoustic Data

The conversion of digital counts to voltage was facilitated by tabulated values of the least significant bit weighting within the seismological recorder configuration software. Table 3 replicates channel properties of the analog-to-digital converter within the seismological recorder. A third channel was digitized on the recorder, which was simply terminated by a 50-ohm resistance. The purpose of recording the third channel was to quantify the magnitude of electrical self-noise by the digitizer.

Figure 4 shows time series of recorded waveforms. Thirty milliseconds are shown of LDV voltage measurements of the baffled pistonphone, microphone coupled with the pistonphone, and recorder electrical noise. On the low end, floor vibrations transduced an RMS voltage around tens of millivolts. Recorder electrical noise was three orders of magnitude smaller. The RMS voltage for the microphone signal provides a direct measure of microphone sensitivity. Given a nominal sound pressure level of 124 dB from the pistonphone, the microphone sensitivity was 46.03 mV/Pa.

Figure 5 shows the overall RMS velocity as a function of time. Each point represents a 1-minute average of the RMS velocity over the course of 3 hours. Initial and final velocities are nearly identical. From the start, the velocity ramps up well above 6000 µin/s, until about 40 minutes into the time series. For the following 80 minutes, the velocity fluctuates dramatically from about 2000 to 4000 µin/s. At about 120 minutes, floor vibrations begin to level off, returning to a state similar to the start of the time series.

Table 3. Analog to digital channel properties of the seismological recorder. The anti-aliasing filter is a linear finite impulse response (FIR) filter across all channels. Least significant bit (LSB) weight is in terms of microvolts per digital count. Given the selected gain setting, peak-to-peak voltage (V_{p-p}) is reduced by a factor of two.

Channel no.	Sampling Frequency	FIR Filter	V_{p-p}	Gain	LSB Weight (µV/c)
1	2000	Linear	40	2	1.650884
2	2000	Linear	40	2	1.645132
3	2000	Linear	40	2	1.644592

Figure 4. Time series of recorded waveforms for the LDV, microphone, and recorder noise.

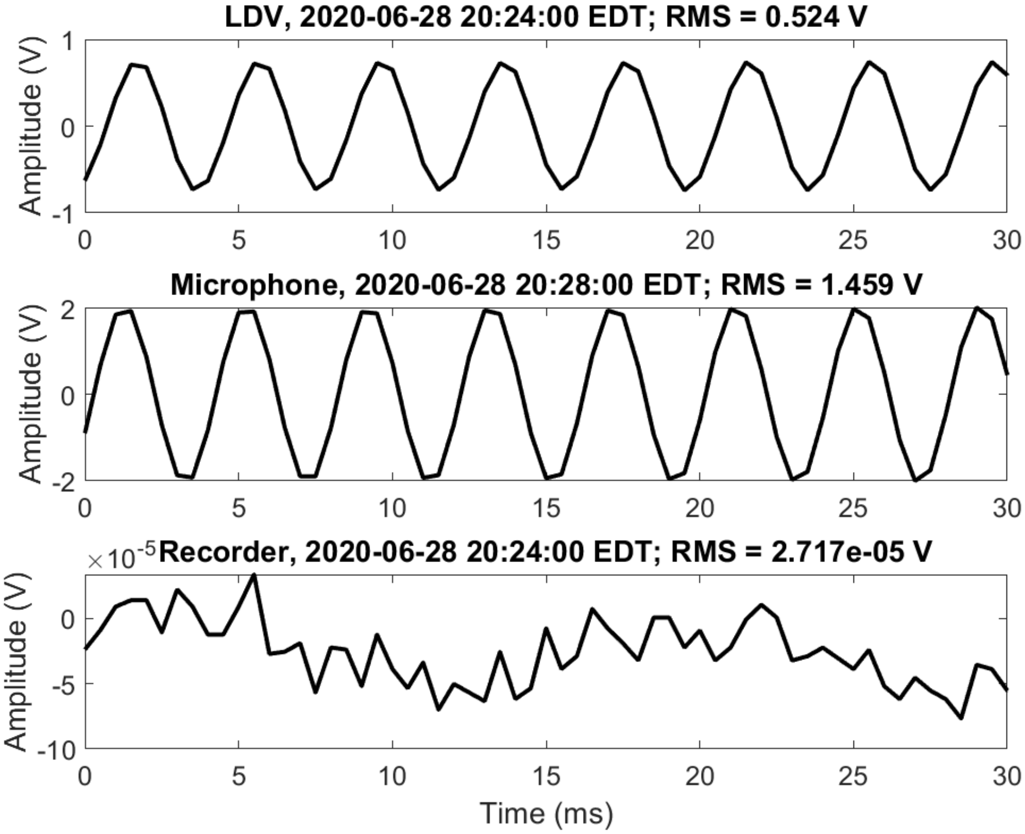
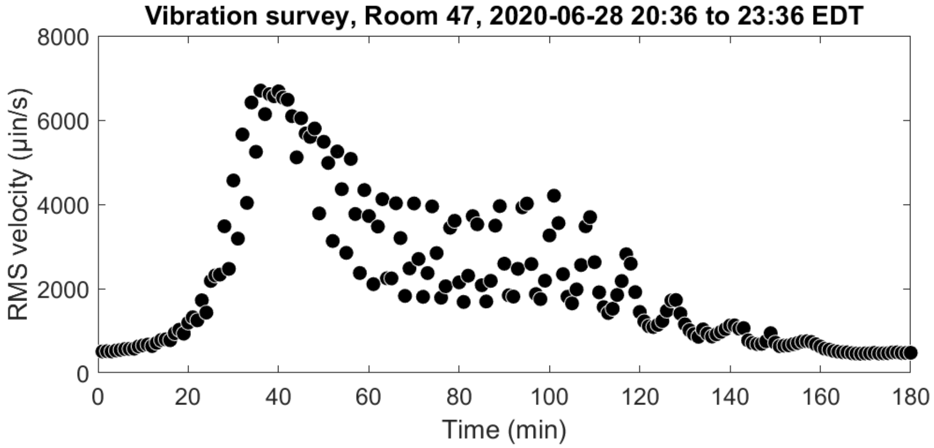


Figure 5. Overall RMS velocity, averaged over 1-minute intervals, as measured by LDV.



The major source of this time-varying behavior is a 56-ton chiller. This relatively new piece of building equipment serves to maintain cold room temperatures one floor above. As cooling loads are detected, a variable-frequency drive ramps up to meet demand. In particular, the drive operates around a frequency range of 40–50 Hz. The overall system has three resonance frequencies, which are skipped over by the electrical drive, causing erratic fluctuations in vibration levels seen in Figure 5. Since the system directly contacts the concrete floor, significant vibrations are transmitted throughout the Main Laboratory Basement floor.

4 Data Analysis

4.1 One-third octave band levels

Vibration and acoustic data were analyzed with respect to long and short time averages of bandpass-filtered time series. The RMS velocity and sound pressure level, per one-third octave band, give a picture of the ambient vibration and acoustic environment. Critically, the required vibration isolation is derived by comparing one-third octave RMS velocity against velocity limits of generic vibration criteria.

Digital filtering of time series data was accomplished by designing one-third octave filters. Eighth-order bandpass Butterworth filters with 3 dB down points specified by one-third octave bandedge frequencies (Acoustical Society of America 2004 [ANSI S1.11-2004]) were designed using MATLAB's digital filtering design tool. A discrete-time, second-order section, direct-form II transposed filter was created for each one-third octave band from 0.63 to 500 Hz (nominal frequencies). Figure 6 shows the transfer function magnitude for the 0.63 Hz band and upper and lower attenuation limits for a Class 0 filter specification (Acoustical Society of America 2004). This filter, along with every other one-third octave band filter, satisfied Class 0 specifications. To meet these specifications for low-frequency bands, it was necessary to decimate the sampling frequency for the filter design (and application). At and below the 2 Hz frequency bands, the decimation factor was 25. At and below the 10 Hz frequency bands, the decimation factor was five.

Application of the one-third octave filters to digitized time series was accomplished via zero-phase forward and reverse digital infinite impulse response filtering. As noted above, for low-frequency one-third octave bands, it is necessary to decimate the time series. Before resampling, decimation was accomplished by filtering data with an eighth-order Chebyshev Type I lowpass filter with a cutoff frequency 80% of the decimated Nyquist frequency. Decimation by a factor of 25 was accomplished by decimating the time series data twice, with a decimation factor of five each time.

Figure 6. Transfer function magnitude of an eighth-order bandpass Butterworth filter for the 0.63 Hz one-third octave band. *Left* plot is a zoomed view of the *right* plot.

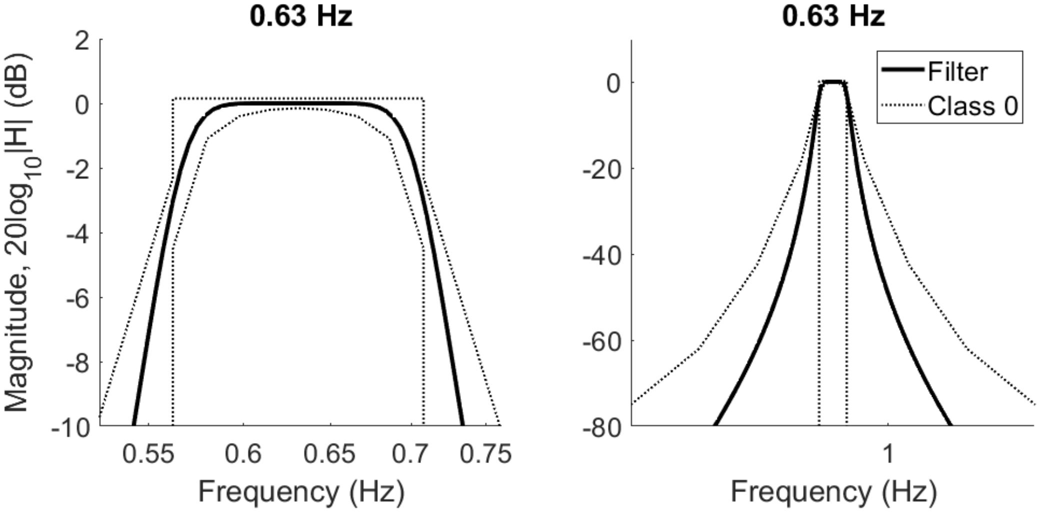


Figure 7 shows the one-third octave band sound pressure level, L_p, averaged over a 3-hour period. The lowest one-third octave band shown is the 2.5 Hz band since the open-circuit frequency response of the condenser microphone is ±2 dB between 2.6 to 20 kHz. The background noise in Room 47 was relatively low. The only prominent source of noise was a table fan, and the time of acquisition was during a weekend night. No particular harmonics dominated the spectrum, and no level exceeded 60 dB (reference 20 μPa). The range of sound pressure levels was from 37 to 58 dB.

Figure 7. Sound pressure level averaged over a 3-hour period.

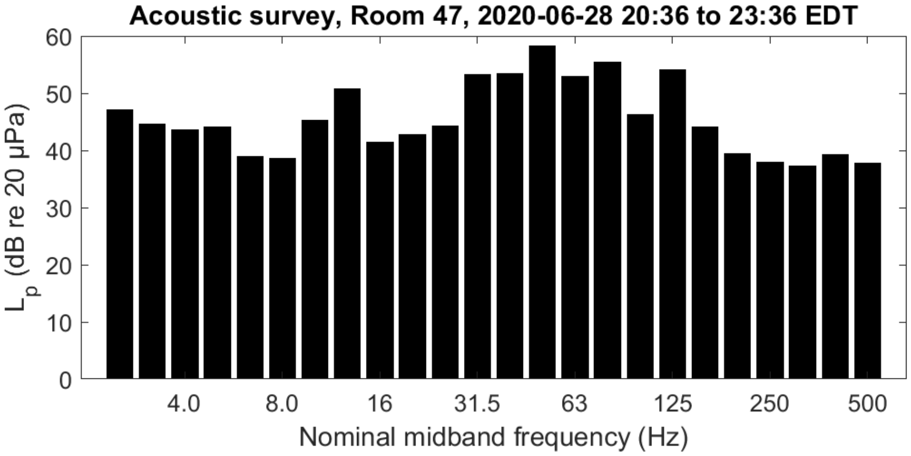
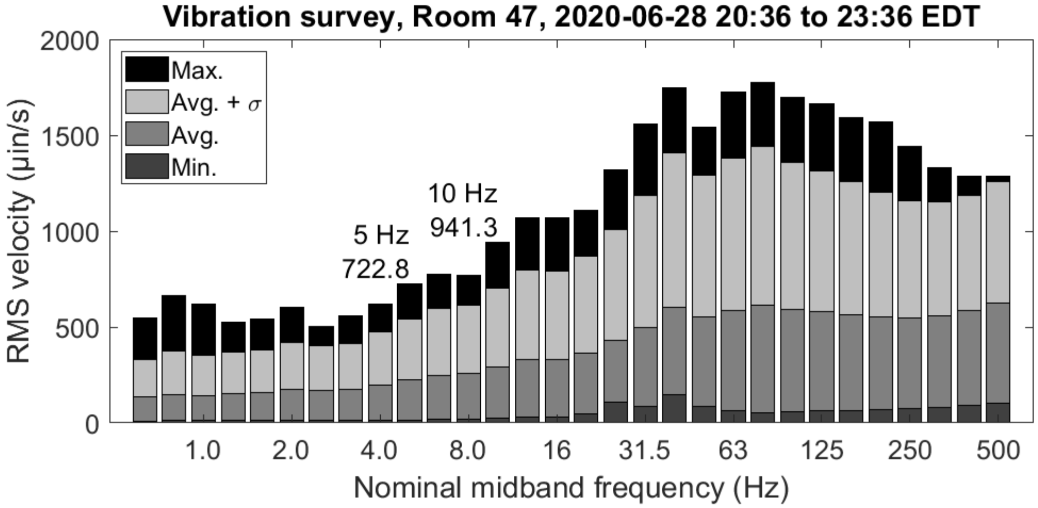


Figure 8 shows the one-third octave band RMS vertical vibration velocity averaged over a 3-hour period. Note that the vertical bars in this figure overlap one another in each one-third octave band. The lowest displayed one-third octave band is the 0.63 Hz band since the frequency range of the

LDV spans from 0.5 Hz to 250 kHz for the given measurement range. The RMS velocity increases nearly monotonically across the lowest one-third octave bands, up to the 40 Hz band. Within this band, vibrations from the 56-ton chiller variable-frequency drive contribute to a local maximum. The range in average RMS velocity spans from 134 to 634 µin/s. Isolation efficiency of optical table support systems are commonly specified at 5 and 10 Hz. For the 5 Hz band, the RMS velocity is 226 µin/s; and for the 10 Hz band, the RMS velocity is 292 µin/s.

Figure 8. Maximum (peak), average plus one standard deviation, average, and minimum one-third octave band RMS vertical vibration velocity over a 3-hour period.



The averaging period affects measured RMS vertical velocities. As noted in Figure 5, the overall vibration velocity changed significantly over the 3-hour measurement period. Considering the 5 Hz one-third octave band, the RMS velocity measured 118, 341, 274, and 226 µin/s, over averaging periods (from the start) of 30, 60, 120, and 180 minutes, respectively. Other statistical measures are important to capture the variation in vertical vibration velocities.

Amick et al. 2005 recommends that in the presence of transient events, measurements be conducted in a "peak hold" mode. Effectively, this is achieved in postprocessing by selecting the maximum measured RMS value in each one-third octave band. Figure 8 shows the peak (maximum) RMS velocity measured during the 3-hour period. The range of peak RMS velocity is from 505 to 1772 µin/s. The peak RMS velocity in the 5 and 10 Hz bands are 723 and 941 µin/s, respectively. Considering the range of peak RMS velocities, the vibration environment can be characterized as falling below the generic velocity limits of vibration criteria (VC) curve VC-

A (a vibration criterion where the tolerance limit is 2000 μin/s across all one-third octave bands) (Amick et al. 2005; Booth 2010).

4.2 Measurement errors

Several sources of experimental error may have been present. For one, vertical alignment of the laser Doppler vibrometer beam can contribute to errors in measuring the vertical velocity. The error is proportional to the cosine of the angle between the true floor normal and laser beam. If the laser beam angle is 3 degrees off the true normal, the error in velocity magnitude would be about 0.1%, fairly small. Another source of error is restricted spatial sampling. Measurements taken at one location may not be representative of statistics for the overall space. Physical access to exposed slab-on-grade was limited, and time constraints limited data acquisition. A third potential source of error is related to the transmissibility characteristics of the tripod supporting the LDV head. The tripod may transmit vibrations to the LDV head, leading to relative vertical vibration measurements rather than true vertical velocity measurements.

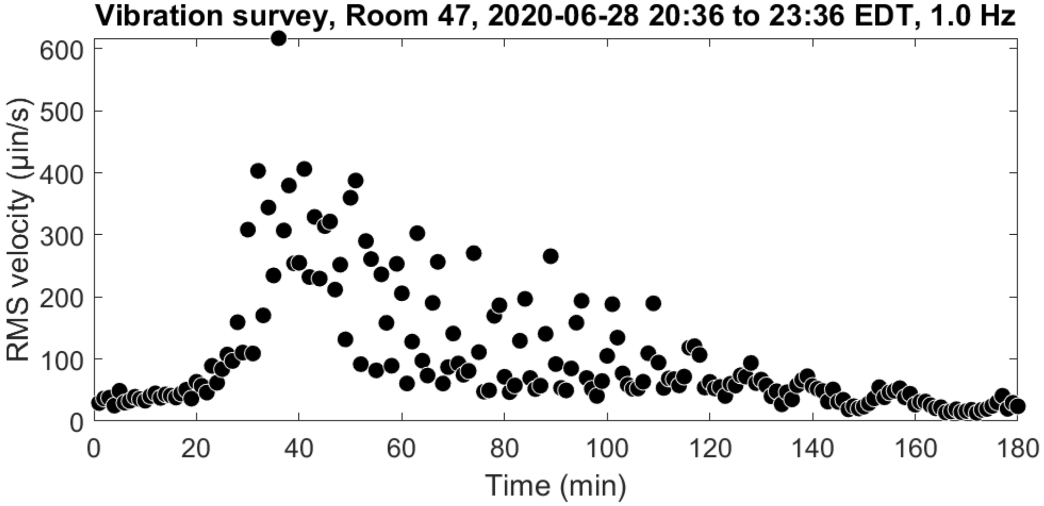
Consider the following single-degree-of-freedom system: a lumped mass in vertical motion due to time-harmonic vibrations transmitted from a rigid base through a spring and damper, in parallel. Since the rigid base moves sinusoidally about its static position, it introduces phase-lagged sinusoidal motion in the mass. The velocity amplitude ratio of the lumped mass to the rigid base is the transmissibility ratio. In general, when the damping factor is relatively small, three important frequency regions of the transmissibility ratio magnitude and phase are pertinent to the issue of measurement error:

1. Well below the undamped natural frequency of the system, the lumped mass moves nearly in synchronization with the rigid base (i.e., rigid-body motion prevails). In this case, relative motion between the mass and base is very small. As a consequence, an LDV mounted to the lumped mass, measuring vertical base vibrations, would measure little to no motion (i.e., the actual amplitude of the rigid base would be unknown).
2. At the undamped natural frequency (resonance) of the system, the lumped mass velocity is amplified and phase shifted by nearly 90 degrees relative to the base motion. The relative motion is primarily governed by the moving mass, and an LDV would not measure base motion.

3. Well above system resonance, the lumped mass motion is dampened and phase shifted by nearly 180 degrees. The relative motion is largely governed by the moving base, with slight amplification by the motion of the lumped mass. An LDV would measure the base motion in slight amplitude error.

Without knowing the resonance frequency of the tripod and LDV head, it is hard to judge if and where transmissibility issues are present. Assuming the lowest measurement frequencies (1 Hz and below) are well below the resonance frequency, it is straightforward to check whether rigid-body motion prevails. Figure 9 plots the 1 Hz one-third octave band RMS velocity, averaged over 1-minute intervals, during the 3-hour measurement period. Comparing to Figure 5 shows that the characteristic ramp up, oscillation, and ramp down in vertical vibrations are captured in this band, as well. This is fairly convincing evidence that rigid-body motion between the floor and LDV head was not present.

Figure 9. RMS vertical vibration velocity averaged over 1-minute periods. Shown for the 1 Hz one-third octave band.



5 Conclusion

Ambient acoustic and vertical velocity measurements were collected in Room 47 of the Main Laboratory Basement. The background noise in the room ranged from 37 to 58 dB over 2.5 to 500 Hz one-third octave bands. The vibration environment can be classified as falling under the generic velocity criteria designation of VC-A, where the tolerance limit is 2000 μin/s.

A useful check against these measurements are direct-contact measurements. Ambiguities in this study may be removed by employing an ultralow-noise seismological accelerometer and amplifier (Booth 2010).

As highly sensitive measurements, like interferometry, will take place in Room 47 and adjoining spaces, the vibration tolerance limit would require vibration isolation below VC-E limits (125 μin/s between 1 and 80 Hz one-third octave bands). Considering the maximum RMS velocity in the 5 Hz (723 μin/s) and 10 Hz (941 μin/s) one-third octave bands, the required isolation efficiency is 83% and 87%, respectively.

Given the ambient vibration environment, commercially available vibration isolation systems can satisfy the isolation efficiency requirements for a VC-E environment. Therefore, within the survey area of the Main Laboratory, it is technically feasible to execute highly sensitive acousto-optic measurements, which will support future research objectives.

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14. ABSTRACT

Plans are underway to create an acousto-optic laboratory on the campus of the Cold Regions Research and Engineering Laboratory. For this purpose, existing space in the basement of the Main Laboratory will be renovated. Demanding measurement techniques, such as interferometry, require a sufficiently quiet vibration environment (i.e., low vibration levels). As such, characterization of existing vibration conditions is necessary to determine vibration isolation requirements so that highly sensitive measurement activities are feasible. To this end, existing vibro-acoustic conditions were briefly surveyed in Room 47, a part of the future laboratory. The survey measured ambient noise and ambient vertical floor vibrations. The ambient vibration environment was characterized according to generic velocity criteria (VC), which are one-third octave band vibration limits. At the time of the survey, the ambient vibration environment fell under a VC-A designation, where the tolerance limit is 2000 μin/s across all one-third octave bands. Under this condition, highly sensitive measurement activities are feasible on a vibration-isolated working surface. The conclusion of this report provides isolation efficiency requirements that satisfy VC-E limits (125 μin/s), which are necessary for interferometric measurements.

15. SUBJECT TERMS

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