Extremely low-vibration experiments with resolutions in the nanometer range supported on air tables may also require a low-noise environment

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ABSTRACT

The paper reports key results from an extensive diagnostic study examining a room's vibration and acoustic noise environments and their correlation to measurement noise. Vibrations of unknown origin were contaminating research being performed on highly vibration-sensitive apparatus in the basement of a recently completed engineering building. The research involved extensive single-molecule microscopy requiring resolutions down to 1 nm carried out on an optical table supported on pneumatic legs. Researchers reported that the experimental noise was of random amplitude less than 40 nm. The problem did not appear to correlate with obvious building or personnel activities. The design vibration and noise criteria for the new space had been VC-E and NC-40, respectively.

At the time of the study, the ambient floor vibrations were several classes better; however, the acoustic environment was slightly worse. FRF correlation was calculated between combinations of the tabletop and floor vibrations and airborne sound. The best correlation was between tabletop vibration and airborne sound. The supply air was a significant part of the problem, but the ceiling offered very little attenuation from above. Some of the sound was being generated above the ceiling by HVAC components other than the supply air.

1. INTRODUCTION

This study was undertaken to identify the source(s) that were disrupting experiments in a recently constructed lab space, and to provide recommendations for mitigation. The experiments had been successfully ongoing at a previous location in another building.

The research team was experiencing intermittent issues with experiments in a basement microscopy lab that had been expected to provide a better environment. The professor's hypothesis was that lab support or general building equipment was creating the problem. The researchers reported that the problem was intermittent, and of varying magnitude, approximately 2 nm peak-to-peak (PP) to

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over 40 nm PP. It appeared to be 24/7, and it did not appear to correlate with obvious building or personnel activities.

The experiments operate on a passive (pneumatic) isolation table. The system is a RM21™ Microscope from Mad City Labs supported on a 4' x 6' TMC CleanTop optical table. It has a highly damped internal resonance above 200 Hz.

The experiments involved measurement of 8 nm steps of motor proteins tagged with gold particles stuck to a glass slide using their microscope at 1000 frames/s, processing to localize the particle position to roughly 1 nm. Position is plotted vs time when the stage is stepped in 8 nm increments every 500 msec (2 Hz). The measurement noise of concern prevented accurate position measurements. Data were digitized at 1000 frames/s (1 msec increments, or 1000 Hz).

The lead author was requested to visit the site and determine what the source(s) may be. It is worth noting that while "vibration" was the term being used by the researchers to characterize the issue (because it appeared that the apparatus was vibrating), there was the possibility that other sources such as acoustic noise and electromagnetic interference (EMI) might be causing the problem.

The researchers carried out measurements during portions of our study, and these digitized results were all subjected to additional analysis, including FFT analysis, along with our own measurements. Our measurement data were processed "live" as well as being and analyzed after the fact.

2. DISCUSSIONS OF DATA ANALYSES

2.1. Analysis of Digitized Experiment Data from Research Team

The researchers' displacement measurements were provided in advance in spreadsheet form and analyzed to transform time domain data to frequency domain, allowing examination for random content and characterization by frequency. The digitizing rates and Nyquist rule dictated that the resulting FFT spectra were good up to about 400 Hz. Two durations were provided (3 sec and 10 sec). The longer duration allowed closer examination at lower frequencies.

The measurement noise in the new space varied widely over time. It ranged in magnitude from 2 nm PP to over 40 nm PP (0.6 nm rms to over 5.5 nm rms). Representative time histories of typical "good" and "bad" measurement periods are illustrated in Figure 1. The raw measurements are shown in blue; the pink represents a moving average used to smooth the data. The green is calculated as the raw signal minus the smooth moving average and represents the measurement error.

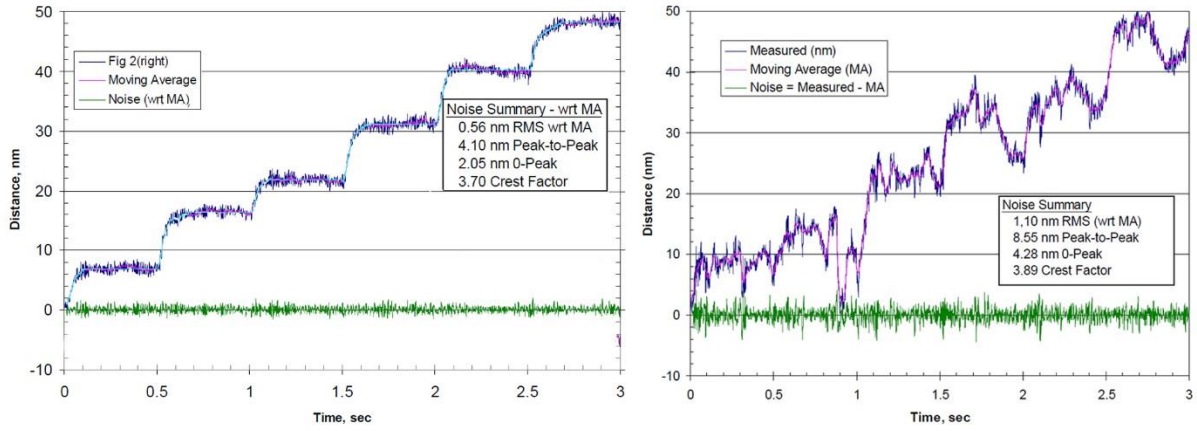

Figure 1: Measurement time histories: "good" period (left) and "bad" period (right). Pink curves show moving averages of each. Green shows the time history of "noise" with respect to the moving average.

Figure 2(left) overlays the two moving averages from Figure 1. Figure 2(right) shows 0-100 Hz FFT spectra of the two moving averages. The primary difference between the two spectra appeared to involve frequency content below about 40 Hz. During acceptable periods, the FFT spectrum tended to roll off with decreasing frequency and the stepping was represented as sharp peaks spaced at 2 Hz. When measurement noise was excessive, the FFT spectrum increased with decreasing frequency over the same range, masking the steps.

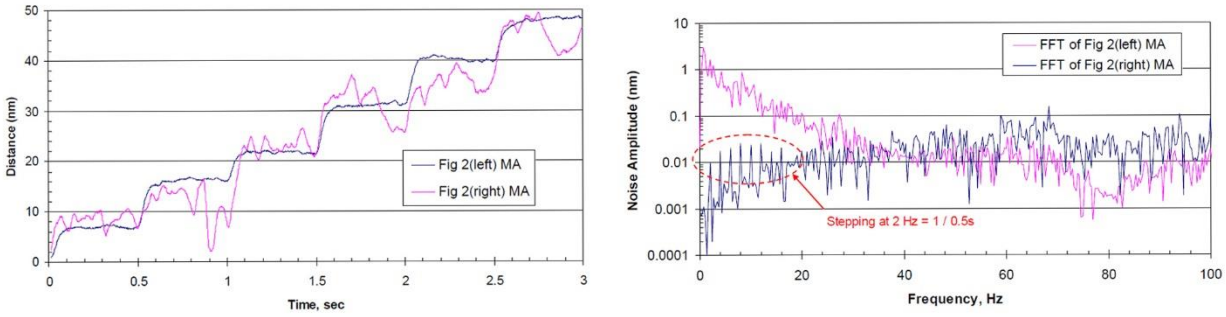

Figure 2: Moving average time histories superimposed (left) and FFTs of each measurement time history (right).

2.2. Measurement of Ambient Conditions and Comparison with Building Design Criteria

The design vibration criterion for the portion of the basement containing the laboratory was VC-E; the noise criterion for the space was NC-40. Measurements of ambient vibration and acoustic noise were carried out in the laboratory with airflow settings in their normal modes and with airflow turned off.

The triaxial floor vibrations for the space measured at the time of this study are shown in Figure 3, along with the VC family of criteria and the NIST-A criterion. The ambient vibrations lie an order of magnitude below the design requirement of VC-E, in fact meeting both the much more stringent VC-H (0.39 μm/s) and NIST-A. Overall, these vibration amplitudes are lower than existed in the old lab in the previous building (0.7 μm/s).

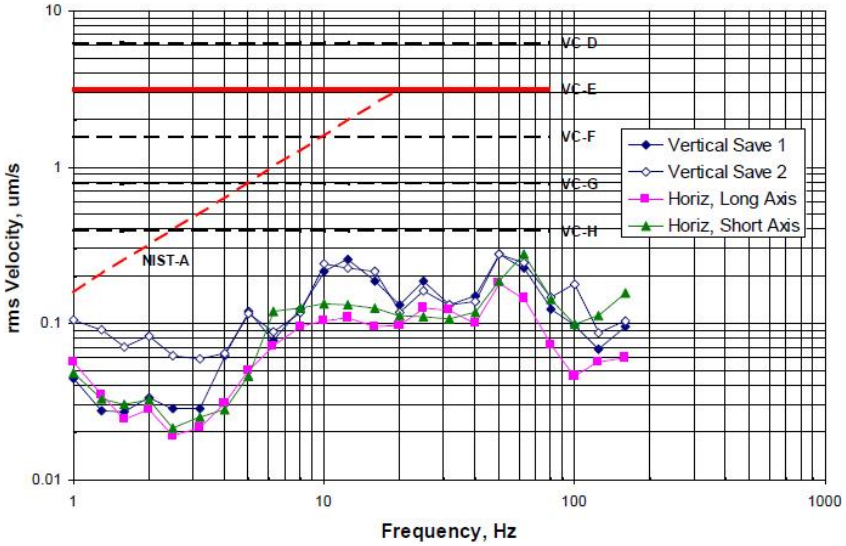

Figure 3: Floor vibration, triaxial ambient

The noise in the room, shown in Figure 4, was found to be above the design requirement of NC-40 in the frequency range characteristic of diffuser or end-point distribution turbulence (1K to 2K Hz), though this will be found to be somewhat irrelevant for the problem at hand. The low-frequency sound (infrasound) is indicated by the spectra shown with solid symbols. They lie well below the extension of NC-40 (shown in red) but are still rather high. In addition, the effect of turning off the supply air, while dramatic at frequencies of 63 Hz and higher, is negligible at frequencies between 2 and 16 Hz.

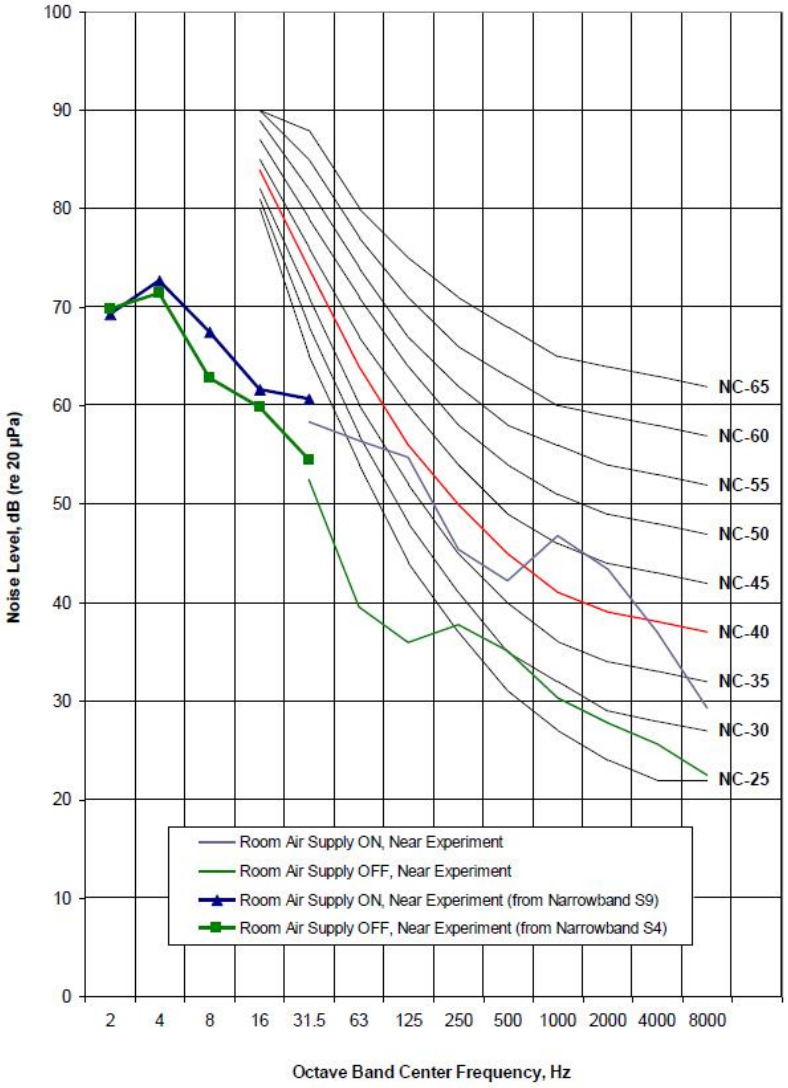

Figure 4: Ambient noise with NC criteria

2.3. Documentation of Mechanical Vibration Sources

Vibrations were measured in the mechanical equipment room along with a visual inspection of the isolation hardware. However, none of these sources was found to be the primary cause of the problem.

2.4. Correlation of Table Vibration with Ambient Floor Vibrations and Heel Drop

Vibrations were measured with one accelerometer placed on the floor and the other placed atop the table — oriented such that the axes of the two accelerometers were parallel with axes oriented vertically. The following quantities were obtained: (a) Acceleration in 0-to-Peak units of g; (b)

Frequency response function (FRF) magnitude; (c) Frequency response function (FRF) phase, expressed in degrees from -180 to +180; and (d) FRF coherence, which is unitless, and has a value between zero and one.

Figure 5 compares results due to ambient conditions (fine lines) and heel drop (heavy lines), measured while room air was ON and legs were pressurized. Spectra are shown for (a) vibration amplitudes and (b) coherence measured on floor (blue) and tabletop (pink). The airspring resonance is at 2.25 Hz, and attenuation occurs at frequencies above about 7 Hz. The frequency range of best coherence (3.7 -8.7 Hz) is indicated with the red bar; under ambient conditions it is 0.13, with the heel drop it is 0.86. When averaged over frequencies between 0 and 150 Hz, the coherence is 0.07 for ambient conditions and 0.194 the heel drop. Under ambient conditions, the magnification at the airspring resonance, denoted Q, is 44, corresponding to a damping of 1.1%; when excited by a heel drop, these values are 79 and 0.6%, respectively.

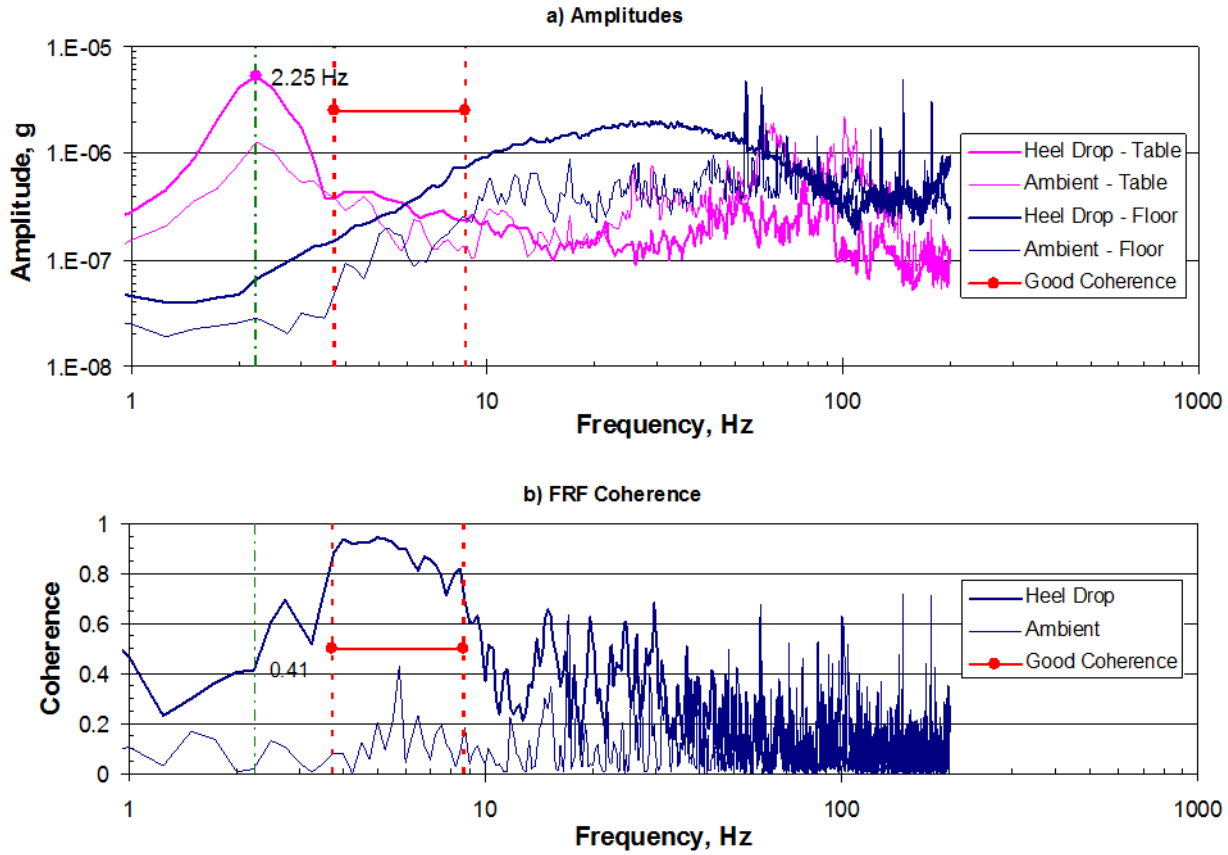

Figure 5: (a) vibration amplitudes and (b) coherence measured on floor (blue) and tabletop (pink), due to ambient conditions (fine lines) and heel drop (heavy lines). Air is OFF.

2.4. Correlation of Table Vibration with Acoustic Noise — Supply Air OFF and ON

These measurements involved the input to one channel being the signal from a microphone (53.9 mV/Pa) calibrated down to 1 Hz and the other channel being the signal from one accelerometer placed atop the table in the vertical direction. The following quantities were obtained: (a) Sound pressure in in units of 0-to-Peak units of pascals (Pa) and acceleration in 0-to-Peak units of g; (b) Frequency response function (FRF) magnitude (in units of g/Pa); (c) Frequency response function (FRF) phase, expressed in degrees from -180 to +180; and (d) FRF coherence.

Because the FRF is of differing units (g/Pa), then we no longer look for resonance peaks *per se* and the notion of amplification is not applicable. Our focus will be more on assessing and comparing coherence.

Figure 6 shows tabletop vibration with supply air OFF and legs pressurized, camera fan was turned OFF and ON. This yielded an average coherence of 0.45 and 0.39, respectively. The only observable differences between these two states are identified with red ovals. These differences were not observable in the acoustic measurements. If the camera fan was contributory to the measurement problem, it was a minimal contribution.

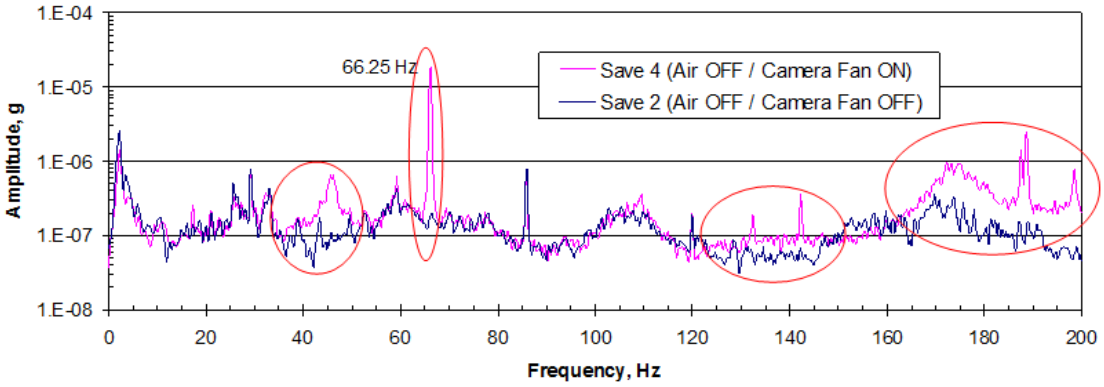

Figure 6: Comparison of tabletop vibration with camera fan OFF (blue) and ON (pink).

Figure 7 shows the correlation of vertical table vibration with three cases involving acoustic noise: (blue) is supply air and camera fan both OFF; (pink) is supply air OFF and camera fan ON; and (green) is supply air and camera fan BOTH ON. Legs were pressurized for all measurements. Values of average coherence for the three cases were 0.45, 0.39 and 0.75, respectively.

Three zones with good coherence associated with supply air are shown: 14-25 Hz, 59-79 Hz, and 87-155 Hz. Three frequency zones remain unaccounted for with this analysis: 0-14 Hz, 25-59 Hz, and above 79 Hz. Part of one of the zones (25-33 Hz) exhibits a high correlation between acoustic noise and tabletop vibration, but none of the sources that could be turned off appeared to affect the tabletop vibration.

3. SUMMARY AND CONCLUSIONS

3.1. Analysis of the Researchers' Measurement Data

Fourier analysis of the sample displacement data from the affected apparatus exhibits several features:

- The measurement noise at space varies widely over time. It ranges in magnitude from 2 nm PP to over 40 nm PP (0.6 nm rms to over 5.5 nm rms).
- The noise appeared to be entirely random at frequencies between zero and 400 Hz.
- The primary difference between Fourier spectra of traces recorded during acceptable periods and those from unacceptable periods appeared to involve frequency content below about 40 Hz.
    - During acceptable periods, the Fourier spectrum tended to roll off with decreasing frequency and the stepping appeared as sharp peaks spaced at 2 Hz, associated with the step rate of the procedure.
- When noise was excessive, the Fourier spectrum increased with decreasing frequency over the same range, masking the steps.

- The Fourier spectra also contained "humps" in the frequency content between 50 and 70 Hz and between 90 and 140 Hz. This appeared to be present under all conditions, good and bad, and may represent resonances in the apparatus itself.
- In time domain, the error seemed to involve a combination of impulsive response and random variation. The maximum error values involved the impulses.

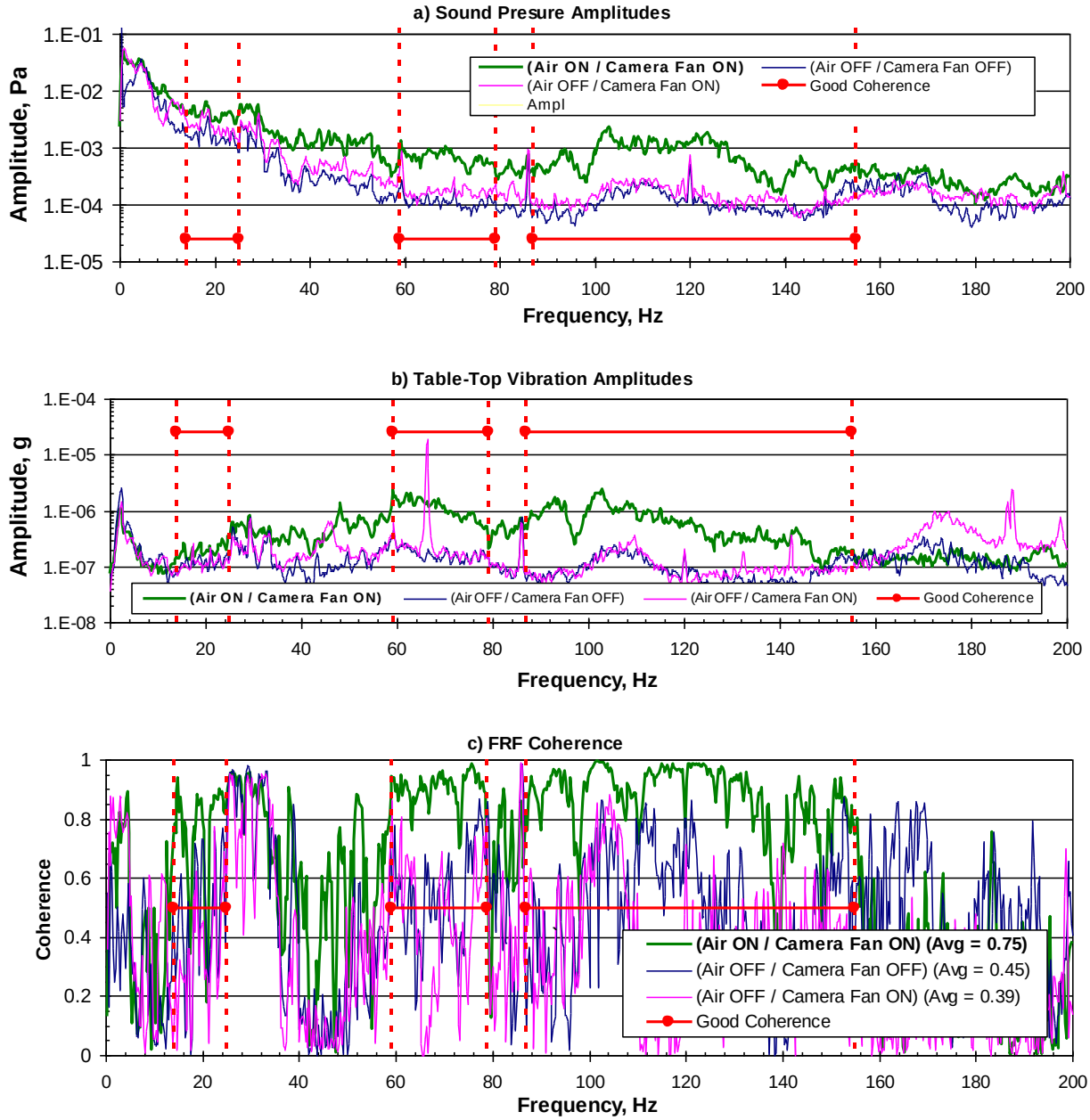

Figure 7: Correlation of vertical table vibration with acoustic noise: (blue) is supply air and camera fan both off; (pink) is supply air off and camera fan on; and (green) is supply air and camera fan both on. Legs pressurized for all measurements. Three zones with good coherence associated with supply air are shown with red bars: 14-25 Hz, 59-79 Hz, and 87-155 Hz.

3.2. Analysis of the Measured Vibration and Acoustics Data

The floor presents an exceptionally quiet environment. It is not the problem.

The problem for the experiment appears to be acoustic noise in the 63 and 125 Hz octave bands (and lower frequencies). The room meets NC-45 in general, and NC-30 in the low-frequency bands. A big "hump" at 1K and 2K bands would suggest diffuser or silencer intake noise, but these are not the frequencies that are interfering with the experiments.

It seems the experiment could work (approximately) simply by shutting off the air. Thus, a simple "solution" is to give the user easy access to do this. However, this can lead to temperature rise in the room over extended periods. Acceptability of this would be up to the researchers as well as consideration of the effect it might have on building operations outside the lab.

3.3. Analysis of the HVAC and Architectural Issues

Some of the issues pertained to variances between the room as designed and the apparent requirements for the experiment, as identified in CGA's review and considering features pertinent to infrasonic acoustics, including:

- The ceiling is acoustically transparent at low frequencies. Even when supply/return air is off there is still some noise and subsequent ripple in the experimental data, though it is approaching "acceptable" at times. Installing a hard ceiling would help reduce noise from sources in the ceiling space that are not in the direct supply and return air path. This includes a 40" x 18" duct (see Figure 8), that passes over the room to supply other areas (it is likely that the walls of this duct could be moving in the pattern we call "oilcan" motion, which could be radiating downward into the room even when the supply air to the room is turned off), VAV casing-radiated noise, and other sources.
- There is a 90-degree flex right at the entrance to the return air silencer, which could cause a problem at higher frequencies in particular. It was shown on the as-built drawings (and this was confirmed in the field). This detail prevents the air from entering the silencer with a uniform velocity profile (which can compromise performance), and it could introduce turbulence.

4. ACKNOWLEDGMENTS

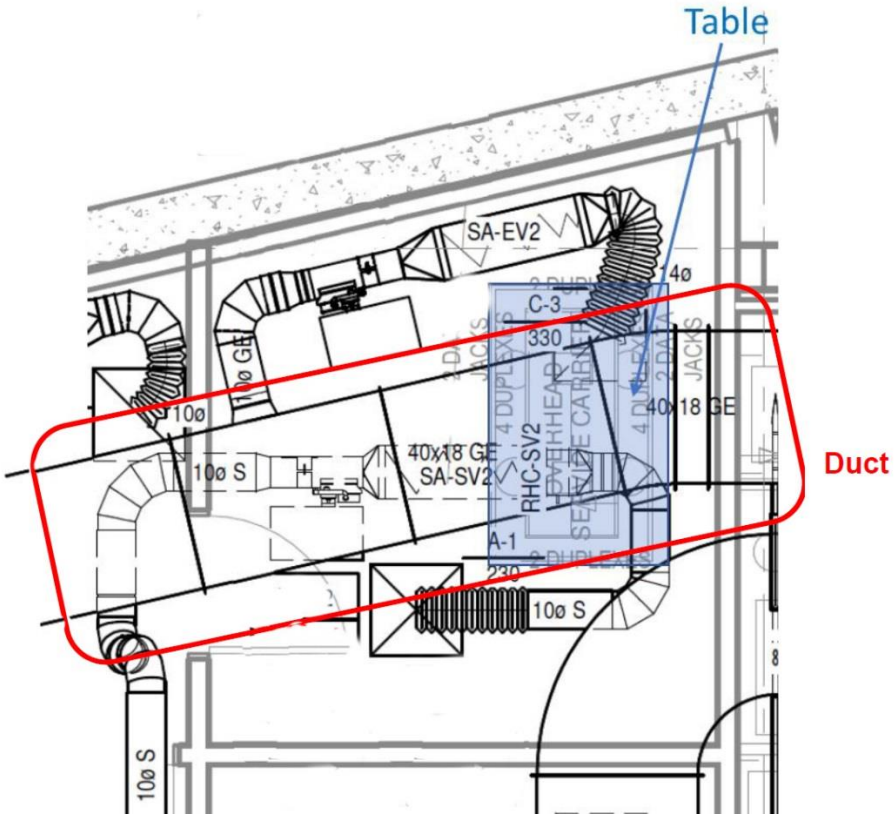

Figure 8: HVAC distribution above the ceiling of the laboratory being studied. The red rectangle indicates the 40x18 inch duct. The blue rectangle indicates the position of the experiment on its table.

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