Baltimore, Maryland
NOISE-CON 2010
2010 April 19-21

Tri-axial measurement of roadway vibration in multiple research buildings located throughout an urban college campus

Scott Harvey[a]
Josh Curley[b]
Phoenix Noise & Vibration
5216 Chairmans Court, Suite 107
Frederick, MD 21703

Erich Thalheimer[c]
Parsons Brinckerhoff, Inc.
75 Arlington Street
Boston, MA 02116

ABSTRACT
Plans are currently underway to construct a mass transit light rail line through the center of a major university campus. Concerns over this significant change to the school's infrastructure were raised by members of the university's faculty, particularly research professors, questioning, among other things, whether their projects and vibration sensitive equipment will be disturbed from vibration generated by the proposed train pass-bys. A study was arranged to investigate the campus's existing vibration levels and analyze the potential for a substantial increase in vibration once the rail line is constructed. This study was primarily a measure of vibration from traffic sources, especially university buses which operate frequently throughout the campus during all hours. The project involved recording simultaneous tri-axial vibration measurements in numerous locations throughout the campus. This required developing methods to manage equipment, make measurements, organize data, and present results in an efficient, timely, and coherent manner. The data documents the level of ambient ground and structural vibration already present from daily university activities and will serve as a basis for comparison to the increased vibration levels, if any, caused by the newly constructed train.

1. INTRODUCTION
Plans are currently underway to construct a mass transit rail line through the center of a major university, making transportation to and from the school easier and more accessible while decreasing the amount of traffic and congestion the institution brings to its surrounding area. As with any considerable change of this magnitude and significance, opinions and suggestions from members of the campus's student body, faculty, and community are being expressed in both support and opposition. Of those on the opposing side are university professors concerned that their research

Email address: sharvey@phoenixnv.com
Email address: jcurley@phoenixnv.com
Email address: thalheimer@pbworld.com

projects and sensitive equipment will potentially be disturbed by the high vibration levels generated by all the new train pass-bys.

A vibration study was conducted by a third party on behalf of the university during the summer of 2008 in an effort to establish ambient vibration levels throughout the campus representative of activities during a typical university day. Measurements were made in several buildings at numerous locations, specifically near vibration sensitive equipment, to determine the average vibration within the buildings.

Results of this study found that average vibration levels throughout the campus were relatively low and comparable to other research institutions and universities. To those proposing the rail line installation, these results indicated that any train activity so close to vibration sensitive spaces would undoubtedly increase building vibration levels since existing levels were already so low. This argument could potentially make approval of the project very difficult given the detrimental effect it might have on important university research and educational facilities.

The rail line proponents considered the findings questionable, specifically since the survey was conducted during the summer when university busses, thought to be the primary source of current vibration levels, operate much less frequently than throughout the semester. They believed the measurements did not fairly represent vibration levels typical of a normal campus day, suggesting that levels would measure higher under different conditions.

In April 2009, Phoenix Noise & Vibration was approached by a company working with the rail line to aid in recreating the initial vibration measurement survey. Vibration levels would be measured in the same buildings as before, as well as in new locations determined to be vibration sensitive by university representatives since that time. This study would more accurately investigate the campus's existing vibration levels, measuring continuously using a longer sampling time and capturing typical campus activity during the semester which would include the busier university bus schedule. Measurement results would then be available to analyze the potential for a substantial increase in vibration once the rail line is constructed.

While the format and scope of this study seemed straightforward, this new study had one major constraint: it was to be conducted by mid-May before classes terminated to avoid further project delays, which meant tri-axial vibration measurements had to be recorded in at least 20 locations across campus in two days. Additionally, the client requested 15 minutes of data for each location and that time histories (i.e. .wav files) be recorded for post-measurement analysis. The strict timeframe and survey guidelines would prove to be the biggest challenge, requiring the development of methods to make measurements, manage equipment, organize data, and present results in an efficient, timely, and coherent manner.

2. VIBRATION MEASUREMENTS

Making low level tri-axial vibration measurements is not possible without the use and coordination of multiple devices. Extensive research was conducted on the instrumentation available to perform such a task within the time allowed.

Three key decisions were made early on in this process:

1. Record full time history data instead of averaging frequency data.
2. Use three accelerometers, one for each axis, instead of one tri-axial accelerometer.
3. Use extremely sensitive accelerometers (10 V/g) to measure the low vibration levels expected from this assignment.

Full time history data was recorded so that it could be evaluated at a later time to reduce the amount of time spent in the field. The time constraint was on the data collection process, not data analysis. Three separate, mutually-orthogonal accelerometers on a mounting block were used because a tri-axial accelerometer with a high enough sensitivity could not be found.

A data recorder (shown in Figure 1) capable of simultaneously recording four input signals was needed to record vibration levels in the x-, y-, and z-axes. The data recorder also needed to be light weight, battery operated for easy transport, rugged for field use, and simple to operate. The data recorder used SD cards to record all vibration data as audio wave files (.wav). Each accelerometer was connected to the data recorder using a coaxial cable and calibrated at the start of each day in the field. The calibration process was absolutely critical to have a recorded calibration signal .wav file for comparison. A special, portable vibration calibrator was used for this purpose which could handle the weight of the accelerometer (50 grams) and would generate a reference quality vibration level of 0.1 g's RMS at 160 Hz.

Figure 1: Rion DA-20 Data Recorder.

The full equipment set used for this analysis is presented in Table 1. Two equivalent measurement systems were assembled, allowing two teams of engineers to collect vibration data more quickly at a greater number of locations. A laptop computer was also used to in the field to back up data at the end of each measurement day.

Table 1: Measurement equipment used throughout vibration survey.

Instrument	Manufacturer	Model	Quantity
Data Recorder	Rion	DA-20	2
Accelerometer	PCB	393B05	6
Vibration Calibrator	MMF	VC100	1

3. EQUIPMENT MANAGEMENT

The three accelerometers, data recorder, and cables had to be connected and organized in such a way that they resembled a single measuring unit which could be set up and moved quickly in the field. This was extremely important if the measurements were to be made in the time allotted. The equipment management method also had to have an element of functionality to it, allowing the accelerometers to measure accurately with little user disturbance.

To address this, three accelerometers were mounted to a 35 lb. steel block (shown in Figure 2), designed in-house to allow for accurate vibration measurements and ease of set up and movement. The steel block was heavy enough to serve as a sufficient mass on which to mount each

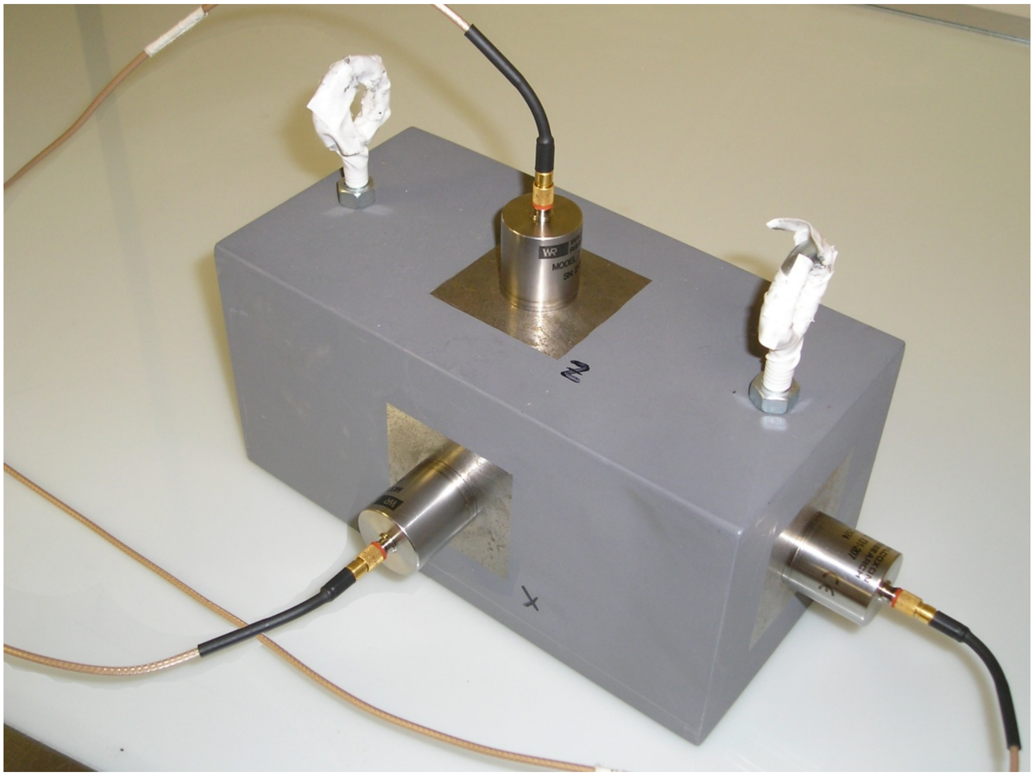

Figure 2: 35 lb. steel block with three mounted accelerometers.

accelerometer, one that would couple with the building's structure without amplifying or damping vibration levels. It also served as a mounting template which only required set up once a day instead of before each measurement. Each accelerometer was mounted to the block at the start of the measurement day using a steel stud screwed into a face of the block. The block was then finished off with a nylon strap handle so that it could be easily handled and carried to each location.

The accelerometer block was then connected to the data recorder in an equally user-friendly manner. To reduce the time required to set up at each location and aid in cable management, the Monster Cable-It (see Figure 3) was used to wrap the three 20-foot cables connecting the data recorder to the three accelerometers. This product allowed the cable set to be laid out, coiled, and transported quickly while protecting them from any field induced wear and damages.

Figure 3: Monster Cable-It cable management product.

3. MEASUREMENT PROCESS

At the start of each day in the field, each accelerometer was placed on the portable calibrator and the resulting calibration signal was recorded on a given channel of the data recorder as a .wav file. This calibration record would later be used during data playback to adjust the sensitivity of the instruments used in the playback process. An accurate calibration record, specific to each accelerometer and cable combination, was required to ensure accurate post-analysis of the measured data.

In each location, vibration levels were measured in 15 minute intervals to capture a sufficient amount of typical campus activity, including at least five bus pass-bys. The steel block was always positioned in the following manner (as shown in Figure 4):

- placed on the building's floor,
- x-axis oriented perpendicular to the busiest adjacent road,
- placed in close proximity to the vibration sensitive piece of equipment within the room.

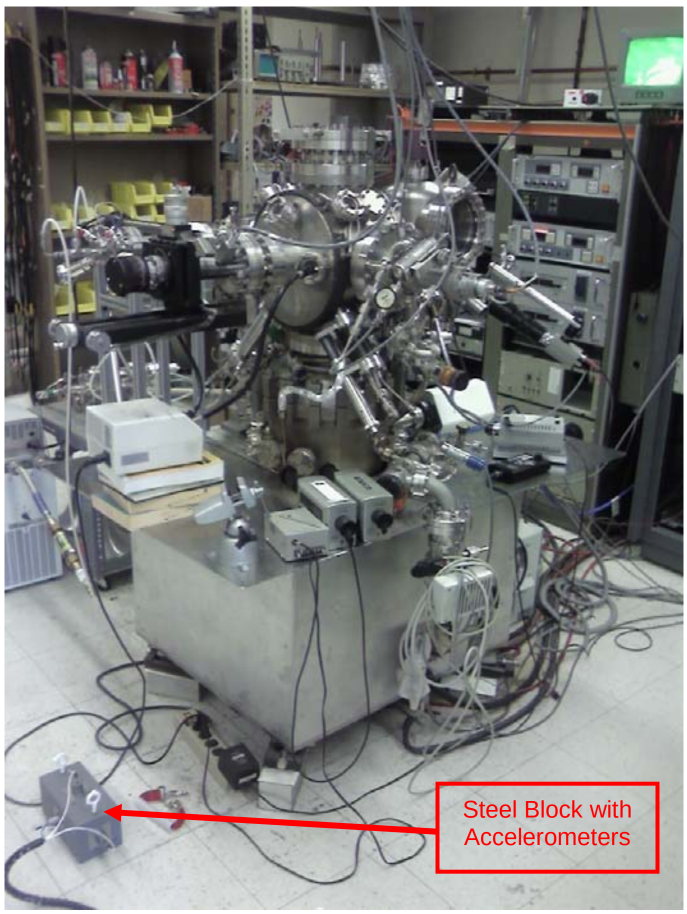

Figure 4: Vibration measurement set up for scanning tunneling microscope.

A field engineer was present for the duration of each measurement, monitoring the data recorder and taking note of which events caused an increase in vibration. The field technician stood away from the accelerometers so that any movement did not affect the data.

In addition to a field engineer operating the data recorder, a field technician was outside the building recording the times of each bus pass-by so that any correlation between these events and an increase in building vibration levels could be attributed to a bus pass-by and not some extraneous occurrence.

4. DATA ORGANIZATION

Detailed field notes were imperative in separating and organizing the recorded data. Each accelerometer's axis, sensitivity, and storage location was documented for each measurement location to ensure the recorded data could be identified and attributed to the correct building, room, and piece of equipment. In all, 30 separate tri-axial measurements were performed near sensitive university devices, resulting in 90 individual data samples; each one of which needing to be recorded and accounted for properly for later analysis.

5. DATA PLAYBACK

The recorded time histories were played back through a device capable of carrying out third octave frequency analysis down to a low frequency cut off below 1 Hz. This was done by connecting the data recorder to a Norsonics 140 sound level meter and calibrating the fdata recorder to play the recorded audio files into the sound level meter while it recorded the data as vibration measured in decibels. Using this process, a separate record was generated for each vibration measurement on the sound level meter. The Norsonics 140 performed this task very well, albeit at a rate of one recorded channel of data at a time.

6. RESULTS PRESENTATION

Following data playback, the decibel data (referenced to 1 micro-G) was converted to linear acceleration data and then mathematically integrated to yield velocity levels in engineering units of micro-inches/second (μin/sec). Several metrics were required from the data recorded at each measurement location, including:

- LfF,99.0%
- LfF,95.0%
- LfF,90.0%
- LfF,50.0%
- LfF,10.0%
- LfF,5.0%
- LfF,1.0%
- LfS(min)
- LfS(max)
- Lfeq

The process of compiling this data was achieved efficiently using an Excel Macro written to extract the pertinent data and insert it into an Excel spreadsheet which converted from decibels to μin/sec, adjusted for the sensitivity range, and graphed the data. Figure 5 presents an example of the graphical representation of the measured and processed vibration levels.

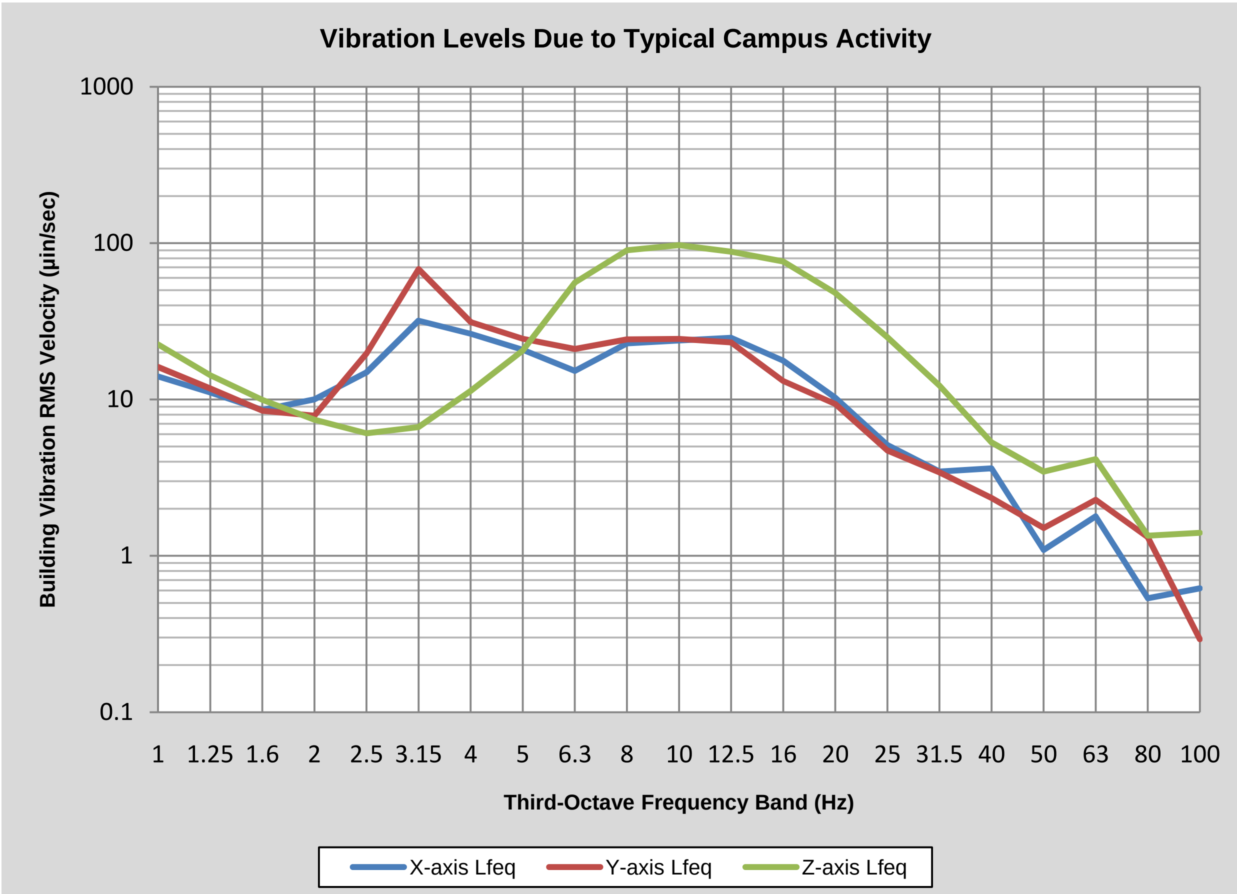

Figure 5: Tri-axial time averaged vibration levels.

7. CONCLUSION

The data collection, management, and analysis processes used in this vibration study were essential to its success, requiring extensive research and planning before the first field measurement was recorded. Detailed notes were kept and carefully formulated procedures were followed so that tri-axial measurements could be made in 30 locations over two days. Once the measurements were made, the data's playback, condensing, analysis, and presentation also had to be meticulously monitored and examined.

At the current time, thanks to this intensive ambient vibration study, the university has decided to forgo their opposition to the rail line's construction. University researchers appear to be more concerned now about induced EMI/EMF from moving light rail vehicles rather than previous claims that it would increase vibration levels throughout the campus.