Monitoring Construction Vibrations at Sensitive Facilities

Marc S. Newmark, **Jeffrey A. Zapfe**, and **Eric W. Wood**, Acentech Incorporated, Cambridge, Massachusetts

Construction-related vibrations, while temporary, still have the potential to disrupt vibration- or noise-sensitive operations in adjacent facilities (such as hospitals, laboratories and low-vibration fabrication facilities). Traditional construction vibration monitors are configured to measure levels corresponding to building damage thresholds. Unfortunately, vibration-sensitive equipment can be adversely affected at levels that are orders of magnitude lower than this. Furthermore, while most construction vibration monitors provide level information at a single dominant frequency, most criteria for sensitive equipment are specified over a range of frequencies. Generally, occupants of buildings near construction sites prefer to continue operations during the construction process. To do this, however, they need to know how the construction-related vibrations compare to their instrument criteria.

New buildings are often constructed in urban environments or campus settings where there are potentially many adjacent facilities that may be affected by the construction process. If any of these buildings contains sensitive equipment, the construction-related noise and vibration can have a significant impact on operations.

If the occupants of adjacent facilities have a vested interest in the project, they may be willing to tolerate the disturbances associated with construction. However, if the facility has no relationship to the new building, disruptions and downtime due to the construction may be unacceptable.

Generally, demolition and excavation are the two phases of construction that produce the most significant levels of vibration in nearby facilities. Noise impacts, particularly those associated with the operation of heavy equipment, can occur almost anytime.

The usual concern related to construction vibration is building damage. A considerable amount of research has been done to define acceptable levels of construction-induced vibration to limit damage to neighboring buildings. Pre- and post-construction inspections and real-time monitoring systems are used to avoid damage claims associated with the construction process. For sensitive equipment, however, the vibration levels of concern are two to three orders of magnitude lower than those associated with even minor cosmetic damage.

In such cases, more sophisticated monitoring systems are needed to measure and assess the potential adverse effects of construction-related vibration. This article describes the evolution of our remote monitoring systems being used for the special case related to noise and vibration in sensitive facilities near construction sites.

Building Damage

In the 1970s and '80s, the U.S. Bureau of Mines[1,2] conducted a number of studies to try to determine "safe" levels of vibrations from blasting. The results of the studies suggested that minor cosmetic damage (cracking plaster, etc.) could be avoided if the ground vibrations at the structure were limited to a peak particle velocity of 0.5 to 2.0 inches per second. Construction projects typically adopt criteria that are somewhere in this range.

Vibration-Sensitive Facilities

Facilities such as hospitals, research laboratories and sensitive manufacturing facilities often contain equipment that can be adversely affected by even small levels of floor vibration. For some instruments like electron microscopes, structurally-radiated noise can also affect instrument operations.

Based on a paper presented at Noise-Con 10, Institute of Noise Control Engineering, Baltimore, MD, 2010.

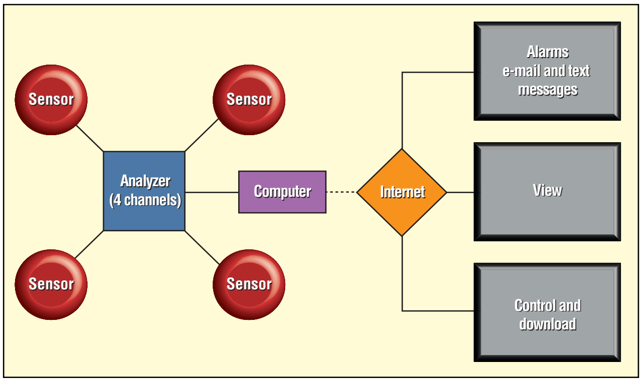

Figure 1. Schematic overview of generic monitoring system.

For most sensitive equipment, manufacturers provide detailed criteria defining acceptable levels of vibration and noise. These criteria are usually frequency-dependent, reflecting the vibration sensitivity of the instrument's internal components.

In cases where specific instrument criteria are not available, generic criteria[3] have been developed to help building designers create structural systems that are appropriately stiff for the intended occupancy. These "vibration criterion" or "VC" curves are still widely used today to design vibration-sensitive facilities. The VC curves can also be used to characterize the levels of vibration that might be acceptable in sensitive areas that might not have specific criteria, such as a hospital operating room. The recommended floor vibration criterion for operating rooms is 4,000 µin/sec (micro-inches per second).

Limitations of Traditional Systems

Traditional construction vibration monitors are designed to measure levels on the order of those associated with building damage. These instruments, were not designed to, and are generally not capable of, measuring the lower levels of vibration that can affect vibration-sensitive equipment. Nor are they designed to report the vibration levels simultaneously at multiple frequencies, which is usually required for comparison to instrument criteria. When these systems are employed to characterize the vibrations near a sensitive piece of equipment, the resulting data often carefully document the electrical noise floor of the monitor but does little to characterize the low-level vibrations at the site.

In general, the type of instrumentation needed to monitor low-level vibration in real-time is the same instrumentation needed to do a site survey before the instrument is installed. (Floor vibration surveys are often performed before an instrument is installed to ensure that the vibration environment is consistent with the manufacturer's criteria.)

Description of Monitoring System

The basic requirements of the remote monitoring systems we employ are:

- High sensitivity – to measure low levels of vibration and noise
- Spectral display – to compare data directly to instrument criteria
- Local storage – data should be stored locally for retrieval at a later time
- Local display – for the benefit of equipment users
- Remote access – internet connection to permit remote control and data download
- Alarms – to provide notification if a threshold has been ex-

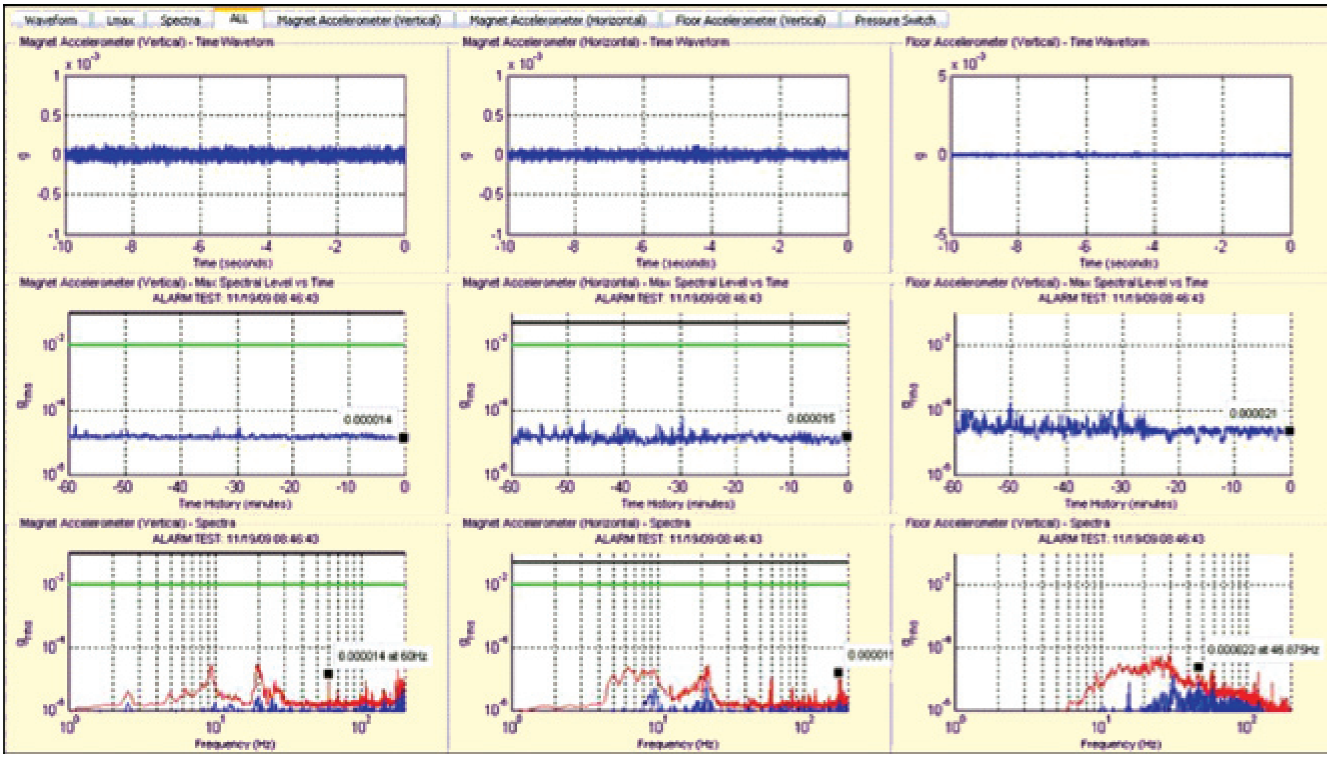

Figure 2. Screenshot of remote monitoring system used in Iowa City.

ceeded
- AC power – power consumption comparable to a laptop computer

Figure 1 shows a schematic overview of our generic monitoring system. The sensors are connected to an analyzer that also provides power to the sensors. The analyzer is connected to a laptop computer that can either be an integral part of the analyzer (the analyzer software runs on the laptop) or it can serve only as a communication device to pull data off the analyzer. The laptop is connected to the internet, which allows remote control, remote data download and a conduit for alarm notifications. Although the laptop has its own internal battery, experience has shown that a surge protector with a built-in battery backup is a worthwhile added layer of protection to ensure that system power is continuous. In the field, the laptop screen is usually open and available for viewing by the users of the sensitive instruments or operations.

Evolution of the Monitoring System

We have used these remote monitoring systems for about three years. In that time, the systems have evolved from a basic remote download and control capability to a fully integrated system with alarms and the ability to store wav files. Evolution of the monitoring systems as they were used on several projects is described below.

Remote Control of Laptop

A key element of the remote monitoring system is the internet connection and the ability to control the computer remotely. The advent of "remote PC" software over the last few years has made this capability easy to deploy in the field without the need for any specialized programming. We use a product called LogMeIn,® but there are a number of remote PC applications that would work equally well.

In addition, wireless internet and cellular data capabilities have allowed these remote systems to be deployed almost anywhere there is internet access. We have deployed systems inside buildings with a wired Ethernet connection and outdoors with only a cellular data connection.

First-Generation System – Research Lab, New York City

The first system that we deployed was a very basic configuration that provided real-time monitoring with remote control and data download. The system sensors were accelerometers attached to five different NMRs (nuclear magnetic resonance spectrometers). Interestingly, the vibration criteria for these systems were not specified on the floor, but they were defined at the magnet supported by vibration isolators. The signals from the accelerometers were fed to a PC-based spectrum analyzer that also provided IEPE power to the sensors. The analyzer software for this system was PC-based, so the laptop was essential to the setup regardless of the internet connectivity. Hard-wired internet connections were provided to allow for remote control of the systems, near real-time observation of the data, and remote data download.

The manufacturer's criterion line was presented on the laptop display for visual comparison, but this system did not have the capability to otherwise determine and notify that an exceedance had occurred.

This particular project was adversarial in the sense that the sensitive facility did not have a vested interest in the new building. The principal concern was excavation, which was going to involve considerable rock removal either by hoe-ramming or blasting.

The monitoring system was installed to satisfy an agreement between the two parties. The availability of the live data in the sensitive facility was a very positive aspect of the monitoring, because it allowed the researchers to confirm in real time that the construction-related vibrations were, in most cases, well within the criterion limits. In this case, the instrument isolation systems also served to attenuate the construction vibrations before reaching the magnets.

Second-Generation System – Hospital, Boston

A large urban hospital in Boston was planning a new ambulatory care center and was concerned that excavation, demolition and pile driving could adversely affect neighboring sensitive areas in the hospital. The closest areas to the site, which were used for imaging (CT, MRI), surgery, and general office space, would be as close as 20 feet from the construction.

The system used here was based on a Larson Davis Model 870 (LD870) environmental monitor. A vibration sensor was connected to the LD870, which was connected to a laptop by way of the RS-232 serial port. We wrote custom software using MATLAB® to communicate with the LD870 and download data continuously for display on the computer. Since the data were being acquired in real time, MATLAB code was also written to compare the levels to predefined criteria. If the criteria were exceeded, e-mail and text messages were sent to hospital personnel.

This was a second-generation system, because it provided the alarm functionality. But the LD870 provides only an overall level; it does not provide spectral information. In this case, that capability was adequate.

The criterion levels were set based on the vibrations measured during a period of baseline monitoring (before construction) and on levels generated during full-scale tests of representative construction equipment.

For this project, the alarms went directly to the hospital's project manager. Not only did the system provide continual peace of mind that ongoing construction was not creating disruptive vibrations, but in cases where excessive vibrations were created, the project manager knew where and when the excessive vibrations occurred before the first complaint arrived. This allowed her to investigate the source of the problem and to take corrective action, if necessary, or to advise users when the activity would be completed.

Third-Generation System – University, Iowa City

Educational facility managers share similar concerns to healthcare managers, namely how construction operations might adversely affect sensitive research labs. If construction-related vibrations result in extended equipment outages, in addition to the inconvenience, this could affect the ability of researchers to meet grant obligations.

The university's principal concern was for a nearby NMR facility. Earlier testing with representative construction equipment had shown that there was a potential for construction-related vibration to reach levels that could damage the magnet.

Since the NMR criteria were based on vibration spectra, a third-generation system was designed that collects spectral information, directly compares it to criteria and sends alarms. We chose to do this using a MATLAB-based signal analyzer for which we could write customized code that would allow us to add the criterion checking and alarm functionality that was needed. In addition, a capability was added to record wav files of the data during the minute immediately before and after the alarm event. The wav files allow for additional post-processing to investigate alarm events.

Figure 2 shows a screen capture of the third-generation system that was used in Iowa City. The system is monitoring three vibration channels, two on the NMR and one on the floor. The floor sensor is important, because it helps distinguish between construction- and nonconstruction-related disturbances (like someone touching the NMR magnet, for example).

In Figure 2, the top display shows the acceleration time waveform for each sensor. The current vibration spectrum, the peak-hold spectrum and the criterion are shown in the bottom display. In this case, the peak-hold spectrum is based on 1-hour intervals, so it is reset every 60 minutes. The middle display shows the greatest spectral levels measured during the previous hour.

If a criterion level is exceeded, an alarm message is sent by e-mail and text message. This particular system is also customized to close a relay, based on the alarm state, to actuate a strobe and an audible alarm bell. Heavy construction began in early 2010, and the university has been using the monitoring system to ensure that the NMR vibrations remain below criterion levels.

The third-generation system also has the ability to provide real-time data summaries to a public or private web page. This allows interested researchers to view a summary of the live data without having to physically log on to the monitoring computer.

References

1. Harry R. Nicholls, Charles F. Johnson and Wilbur I. Duvall, "Blasting Vibrations and Their Effects on Structures," U.S. Department of the Interior, *Bureau of Mines Bulletin 656*, 1971.
2. Mark S. Stagg, David E. Siskind, Michael G. Stevens and Charles H. Dowding, "Effects of Repeated Blasting on a Wood-Frame House," U.S. Department of the Interior, *Bureau of Mines Report of Investigations 8896*, 1984.
3. Thomas M. Murray, David E. Allen and Eric E. Ungar, "Floor Vibrations Due to Human Activity," *AISC Steel Design Guide Series 11*, 1997. SV

The author can be reached at: ewood@acentech.com.