It’s no secret that the construction of a new building or the renovation of an existing building involves activities that generate a considerable amount of vibration. Although this is a necessary by-product of the construction process, the ensuing vibrations can have a negative impact on neighboring facilities, particularly those that house vibration-sensitive equipment and activities. The willingness to endure intrusive vibrations usually depends on the occupant’s vested interest in the end result. Researchers moving into the new building may be more tolerant of the vibrations than people who have no vested interest in the project, or worse have no connection to the institution doing the construction. It’s not uncommon to have a new building project generate opposition with neighboring stakeholders. It’s obviously in the best interest of all parties to avoid this.

**How sensitive is sensitive?**

Vibration monitoring is usually done as a part of the construction process, especially if there are neighboring buildings that could be damaged by construction-related vibration. Conventional construction monitors are configured to measure the levels of vibration that could cause even cosmetic damage to nearby buildings. A construction monitoring program is usually accompanied by pre- and post-construction crack surveys to document damage. Many building codes define acceptable levels of ground vibration...
anywhere from 0.5 to 2 in/sec. These levels are high and can easily be felt by people. As a point of reference, the threshold of human perception is about 0.004 in/sec.

Sensitive instruments are much more sensitive than people. For example, criteria levels for electron microscopes can be as low as 0.000012 in/sec, far below where people can feel them. Most instrument criteria are also frequency dependent, meaning the critical level depends on the frequency of the vibration. Figure 1 shows the vibration criterion for an electron microscope. Because equipment vibration limits are so low, they are often expressed as micro-inches/second (min/s). The dependence on frequency is also evident; this instrument is 10 times more tolerant of vibration at 25 Hz (cycles per second) than it is at 5 Hz.

The limits in Figure 1 are given in terms of vibration velocity, however not all instrument criteria are expressed this way; some use acceleration, others use displacement. Fortunately, it’s possible to convert between units.

Another thing to note about Figure 1 is the frequency axis. 1/3 octave frequency bands are unique because the bandwidth gets wider as the frequency gets higher. For example, the band centered at 5 Hz contains all the vibration energy from 4.47 to 5.62 Hz (1.15 Hz wide), whereas the band centered at 25 Hz contains all energy between 22.4 and 28.2 Hz (5.8 Hz wide). 1/3 octave frequency bands are commonly used to describe vibrations in sensitive facilities. The lettered lines in Figure 1 refer to vibration criteria (VC) designations that are used to classify sensitive spaces. VC-A corresponds to 2,000 min/sec and is appropriate for general lab areas and vivaria. VC-E corresponds to 125 min/sec and is common in semiconductor manufacturing and nanotechnology facilities. To achieve VC-E, the floor is almost always slab-on-grade construction. The VC curves are useful because they provide building designers with generic criteria. This is particularly important early in the design process when specific instruments may not yet be identified.

**What can be expected inside the building?** There might appear to be a disconnect between the allowable vibrations outside a building and the vibrations inside that may affect sensitive equipment. A construction criterion of 500,000 min/sec (0.5 in/sec) outside doesn’t seem to be compatible with an instrument criterion of 125 min/sec inside—in general the two criteria aren’t compatible.

Attenuation plays a part as construction-related ground vibrations pass into the building. Factors that affect this include the soil type, the mass of the building and the depth of the foundation. For a small building with a ground-level, grade-supported slab, the vibrations inside might only be ½ to ¼ of the levels outside. For a large building with a basement, the vibrations inside at the lowest level might be 10 or more times less severe than those outside at ground level. Even a 10-fold attenuation isn’t enough to reduce 500,000 min/sec outside to 125 min/sec inside. Fortunately, while 0.5 in/sec might be the criterion level according to local code, this vibration is only realized during the most intense operations such as pile driving, hoe-ramming, soil compaction and blasting.

Most other construction activities don’t generate vibrations nearly that high. So for a majority of the construction project, the ground vibrations will be much lower—meaning low vibration spaces inside the building can coexist with most construction activity. Even so, 125 min/sec inside is still a very low level and electron microscopes are most often impacted by even modest construction activity. In such cases off-hours scheduling may be the only way to use the instruments during the construction process.
There’s one other important distinction between vibration inside and outside. The outside criterion is commonly expressed as a peak particle velocity (PPV). PPV is a measure of the time waveform, which looks much like the squiggle on a seismograph plot that’s produced by an earthquake. In simple terms, the PPV corresponds to the maximum peak in the waveform. By contrast, the instrument criteria correspond to the frequency distribution (spectrum) of the energy in the waveform. The sum of the energy in the frequency spectrum equals the energy in the time waveform. So, by definition, the spectrum levels have to be lower than the PPV level. This is why it’s critical to measure the vibrations inside the building in the correct units, using the correct frequency bands, as specified by the instrument criterion. It’s also why it isn’t consistent, and may be misleading, to compare PPV values directly to instrument criteria.
Predictions and simulation tests
Late in the design process is usually when the question of potential construction-related impacts to neighboring facilities is first raised. It’s possible to generate reasonable predictions of the construction vibration. The most accurate prediction method uses representative construction equipment at the site to generate vibrations, which are then monitored inside nearby sensitive facilities. Not only does this give a good indication of what vibration to expect during construction, but it also allows the occupants of those facilities to experience the vibration. The next best way to obtain predictions is to use a large drop weight to excite the ground at the site while the response is measured inside the nearby facilities. The measured vibrations can then be scaled based on the equipment used during construction. Finally, the least accurate way to make predictions is to use analytical models for the source, the soil and the building response. The problem with this is little is known about these items with precision.

Monitoring during construction
In the context of this article, monitoring during construction refers to the constant, real-time measurement of construction-related vibrations inside the sensitive facility. The basic objectives of monitoring during construction are to provide a historical record of the vibrations, notify interested parties when pre-set limits are exceeded and broadcast the vibration levels to interested parties in real time. These three objectives feed into one overarching goal to have the construction and the sensitive activity coexist.

Instrumentation
It’s critical to measure the floor vibrations in terms that are consistent with the sensitive equipment. The sensor (usually an accelerometer) should have the sensitivity to measure very low levels of vibration. These sensors are typically much more sensitive than those used for conventional construction monitoring. The other critical component is the analyzer, which receives the vibration signal from the sensor and decomposes it into its frequency components. The analyzer is necessary because, as Figure 1 shows, most instrument criteria are frequency dependent, so multiple frequencies need to be measured simultaneously. Most frequency (or spectrum) analyzers are able do this.

The final link in the chain is a computer. The computer may be needed to operate the analyzer and certainly to store the data, but more importantly it is needed to provide a communication conduit.

Communication
The difference between a real-time system and a passive recorder is the connection to the outside world. Given the widespread connectivity offered by both wired and wireless networks, an Internet connection is usually readily available. The Internet link is critical because it allows the system to be operated remotely, minimize human access, have data downloaded remotely, provide warnings and alarms by way of text message or email and stream data in real time to a Website for viewing.

Data storage and display
The data is stored locally on the system computer. In the most typical application, the local data is downloaded periodically to a server for archiving. If a more short-term backup of the data is desired, this can be done using a commercial cloud storage service.
The display on the local computer represents the data exactly as collected by the analyzer. In general, the local display contains far more data than could be sent to a Webpage in real time, so a subset of the data is provided for transmission to a Web server. The data subset is sufficient to provide a good indication of the current conditions or historic levels.

Website access is usually controlled and made available only to those who need to view the information. Access to the local computer is even more restricted.

The contractor is typically provided with the live Web feed to be monitored on a tablet computer at the site. It’s not uncommon for a contractor to take proactive action to correct a vibration issue before the owner’s project manager even becomes aware of it.
**Warnings and alarms** Once criteria are established they can be loaded into the computer. There are typically two levels specified, the alarm level when the criterion is exceeded and the warning level when the vibrations are “getting close” to the alarm level. If either condition is reached, an email or text message will deploy reporting particulars of where the event occurred and the measured level.

The distribution list for alarms and warnings is usually limited to the contractor, the owner’s project manager and the monitoring system operator. The response procedure to an alarm is determined ahead of time.

**Case study: Boston Medical Center (BMC)** At BMC, construction work was planned in an area about 20 ft away from heavily used imaging (CT, MRI), surgery and office spaces (Figure 2). Criteria were developed based on baseline measurements that were made before construction started. In this case, alarm messages went only to the owner’s project manager. With the advanced warning provided by the monitor, the project manager was able to know where and when excessive vibrations occurred before receiving the first telephone complaint from building occupants. The project manager was also able to contact the contractor to either have them take corrective action, and/or find out how long the disturbance would last. When the vibrations were low, the system gave the project manager peace of mind knowing that ongoing construction wasn’t causing disruptive vibrations. When the vibrations got too high, the project manager knew early on and could advise the affected departments when the disturbance would be over.

**Case study: Univ. of Iowa** Construction of the new Pappajohn Biomedical Research Building was recently completed at the Univ. of Iowa (Figure 3). An active research lab housing a highly sensitive NMR lab was situated next to the construction site. Monitors were installed inside the NMR lab. In addition to the traditional Internet alarms, the systems were also equipped with a horn and a strobe light located outside the lab building. The horn and strobe were used to notify equipment operators when limits inside the NMR lab were exceeded so that corrective action could be taken to reduce the vibration.

**Summary**

The impact of construction on neighboring sensitive facilities can be made more tolerable using real-time monitoring of construction-related vibration. When monitoring is performed in sensitive areas, using equipment that’s appropriate for measuring low levels of vibration, it’s possible to have construction and sensitive research coexist.

Jeffrey A. Zapfe, PhD, is the president of Acentech Inc., an acoustics/vibration/audiovisual consulting firm located in Cambridge, Mass.