

# PC-BASED MEASUREMENT AND ANALYSIS OF TRAFFIC VIBRATIONS

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## INTRODUCTION

The purpose of this paper is to present the general requirements and procedures for measurement and analysis of traffic-induced vibrations and to discuss the methods that are currently in use at IRC/NRC. The following topics are addressed: (i) measurement systems with special emphasis on recording of vibration signals using portable multi-channel PC-based data acquisition systems (ii) 1/3 octave spectrum analysis and frequency weighting of vibration time-histories using digital filtering on PCs, and (iii) measurement practices such as transducers, mounting methods and sampling rates.

## MEASUREMENT SYSTEM

Instrumentation for the measurement of vibration signals usually consists of the following components: (i) vibration transducers, (ii) signal conditioners, and (iii) recording equipment. The characteristics of the complete measurement system should be appropriate for measuring and recording vibration signals in the frequency and amplitude ranges of interest, e.g. a flat frequency response, flat amplitude response, linear phase shift, sufficient resolution and sensitivity, low noise level, sufficient dynamic range, and appropriate environmental operating conditions. For vibrations induced in buildings by road and rail traffic: (i) frequency range is generally from 4 Hz to 80 Hz; sometimes up to 125 Hz, and (ii) amplitudes are in the range 0.005 to 2 m/s<sup>2</sup> for acceleration and 0.05 to 25 mm/s for velocity. It is recommended that the noise level introduced by the complete measurement system be at least 10 dB below the minimum anticipated vibration levels and the dynamic range of the system be greater than 40 dB.

**Vibration Transducers.** Either velocity and acceleration transducers, also known as geophones and accelerometers, respectively, can be used for the measurement of traffic-induced ground and building vibration. The characteristics of geophones and accelerometers vary widely from one manufacturer to another. The appropriate transducer type should be selected according to the frequency and vibration amplitude ranges which are of interest or anticipated. At present, the use of accelerometers is becoming more widespread than geophones because of their wide variety of types and ranges.

Accelerometers are generally classified into two types: (i) deflection type, and (ii) servo null-balance type. Deflection type accelerometers utilize mechanical spring restoring forces and are usually identified by the type of transducer element they utilize, e.g. potentiometer type, strain-gauge type (includes piezoresistive transducers), and piezoelectric type. The higher the sensitivity of deflection-type accelerometers, the greater is their mass. Servo-type accelerometers, on the other hand, utilize servo electromagnetic restoring forces, i.e. "electrical springs", to maintain a mass element in almost a zero-position. Servo accelerometers provide good accuracy, especially at low frequencies. They have very low acceleration thresholds and high sensitivity even though their mass is small. The particular type used by the authors has an acceleration threshold equal to 1 µg, selectable sensitivity (up to 10 V/g), a resonance frequency greater than 800 Hz, and a weight of about 175 grams which includes an aluminum mounting base.

**Signal Conditioners.** Signals from vibration transducers are passed through signal conditioners before they are displayed or recorded to perform the following: (i) to amplify the voltage output of vibration transducers so that it is sufficiently above the

noise level of the display or recording system, and (ii) to eliminate noise or undesired vibrations outside the frequency range of interest. It is advantageous to have the following signal conditioners: (i) amplifiers with gain settings at several values, (ii) a high-pass filter with a cut-off frequency at about 1 Hz to remove any DC offset and eliminate low frequency drifting, and (iii) a low-pass filter with selectable cut-off frequencies to remove unwanted noise above the frequency range of interest and to avoid frequency aliasing during analog-to-digital conversion of vibration signals. Signal conditioning hardware can be of the stand-alone type or included in a self-contained data acquisition system as described below.

**Data Recording.** Vibration signals can be recorded directly in digital form using modern portable PC-based systems. Recording the data directly in digital form offers speed and convenience and the opportunity for on-site inspection and analysis of data. PC-based data acquisition systems also have the advantages of being self-contained, flexible, readily upgradable, and relatively inexpensive. On the other hand, recording the data in analog form is advantageous since the signals can always be re-digitized differently in the future if needed, or used as a back-up to the PC system.

Data recording can also be performed using hand-held "vibration meters". These devices usually provide a single vibration descriptor, e.g. rms or peak level of the frequency weighted vibration signals that can be readily compared with satisfactory vibration levels provided by relevant standards. It must be ensured, however, that the weighting and averaging procedures are appropriate for the evaluation of transient vibration.

**PC-Based Data Acquisition Systems.** Portable PC-based systems can be integrated using commercially available multi-channel analog-to-digital (A/D) conversion boards, and multi-channel signal conditioning boards. These boards, which are software controlled, fit into standard expansion slots inside PCs. Many makes of these plug-in A/D and signal conditioning boards do not require software programming by the user.

Essential features of a system for multi-channel measurements of traffic vibration might be as follows: 8 to 16 channels, sampling rate of 1000 Hz/channel, 12-bit resolution, A/D board with built-in amplifiers with gains at 1, 2, 4 and 8, signal conditioning boards with gain amplification at 1, 10, 100 and 1000, and anti-aliasing filters with a cutoff frequency between 100 and 200 Hz and attenuation rate of about 70 dB/octave or greater. The above combination of gain settings on the A/D and signal conditioning boards provides a versatile selection of gains which is beneficial for utilizing most of the voltage range of the A/D board to increase the signal-to-noise ratio. Preferably, it should be possible to select gain settings for each channel individually in order to accommodate any wide variation in vibration levels at different measurement locations when performing multi-channel measurements.

One of the PC-based systems that is used by the authors features 16 channels, 12-bit resolution, 400 KHz total sampling rate, simultaneous-sample-and-hold (SSH) capability to reduce inter-channel sampling/conversion delay, pre-trigger capability which is useful for unattended measurements, A/D board with gain amplification at 1, 2, 4 and 8, signal conditioning boards with gain amplification selectable in linear increments from 1 to 200, and anti-aliasing filters with an attenuation rate of 80 dB/octave and a cutoff frequency selectable from 1 Hz to 100 KHz. All components are driven with a single data acquisition

software package and fit into a "lunch-box" type PC. This system was optimized for several applications including traffic-induced vibration.

## ANALYSIS OF VIBRATION SIGNALS

The degree of detail required in the analysis of traffic-induced ground and building vibration signals depends on the nature and purpose of the investigation. For a preliminary evaluation of the effect of vibration with respect to human response and building damage it might be sufficient to just find the peak of the vibration signal and determine the predominant frequency of vibration by simply counting the number of negative and positive peaks in a given time interval. For in-depth evaluation, however, 1/3 octave band analysis, frequency weighting of acceleration signals, and spectral analysis have to be performed.

**General Digital Signal Processing.** Digital signal processing and analysis can be performed conveniently using several commercially available user-friendly PC software. The software packages typically include the following signal processing and analysis functions: low-pass/high-pass/band-pass filtering, signal extraction and concatenation, algebraic functions, FFT analysis and spectral estimates, e.g. auto-spectrum, cross-spectrum, transfer function, and coherence function. Some software packages support the creation of macro commands, i.e. command sequence, which are very beneficial for automating lengthy tasks and the processing and analysis of large amounts of vibration signals. For example, the authors obtain velocity from acceleration time records by integrating the latter indirectly in the frequency domain using a macro command that performs the following procedures: extract 50% overlapping segments from the time record, perform an FFT with a Hanning window on each segment, set FFT components below 2.5 Hz to zero, divide FFT components above 2.5 Hz by frequency, inverse modified Fourier spectra (IFFT), and finally, add time segments using 50% overlapping. The macro can be run on selected channels or all channels in a data file.

**1/3 Octave Analysis.** PC software was developed for performing 1/3 octave analysis (Al-Hunaidi et al., 1992) using recursive digital filters which conform to specifications by the standard ISO 2631/2 (1989) for evaluation of human exposure to vibration in buildings. This software can be run in both interactive and batch modes. The latter makes it possible to automate the analysis when a large number of data files have to be analyzed. For instance, both 1/3 octave analysis and frequency weighting (see below) of vibration data collected from 42 runs of test vehicles involving 11-channel measurements, 30 seconds each, were completed in less than 2.5 h on an IBM-compatible 486 DX PC (clock speed of 50 MHz). Similar analysis using conventional analyzers would have taken several days to several weeks. The software can accommodate up to 16 channels and can deal with several processing parameters specified by the user, such as format of data files, channels to be analyzed, and frequency range of the 1/3 octave spectra. Other information such as sampling frequency, sensitivities and gains of instrumentation are read directly from header files created by the data acquisition software. The user can also specify how the signals should be processed, including integration time, start time, and number of initial integration windows to be ignored. Currently, this program can only access data files created by two different commercial data acquisition software packages; however, it was written in modular form so that it can be easily modified to access files acquired with other software packages.

**Frequency Weighting.** Several options for frequency weighting of acceleration time histories is incorporated in the above software. These were realized using recursive digital band-limiting and band-pass filters which conform to specifications in ISO 8041 (1990) and BS 6841 (1987). The use of frequency-weighted vibration levels is the preferred analysis method by several standards for the evaluation of human exposure to

vibration in buildings, e.g. ISO 2631/2 (1989) and BS 6472 (1984).

## PRECAUTIONS DURING MEASUREMENTS

Vibration transducers should be mounted on the ground or on building components using mounting methods which are capable of faithfully transmitting to the transducer the actual motion of the ground or building components over the frequency range of interest. If the mounting method is suspected of distorting the motion, alternative methods should be tried and compared. For ground vibration measurements, the standard ISO 4866 (1990) suggests fixing vibration transducers to a stiff rod (having a diameter not less than 10 mm), driven into the ground. The use of a tapered stake having cruciform section (Al-Hunaidi & Rainer, 1990; Nolle, 1978) is believed to provide a more reliable method than that suggested by the ISO standard.

Precautions should be taken against inductive pickup, electrostatic pickup, and ground loops. These can cause large spurious vibration signals often concentrated at the power-line frequency. Instruments should be properly shielded to decrease electrostatic interference; transmission cables should be twisted conductors wrapped in foil to reduce both inductive and electrostatic pickup; and the complete measurement system should be grounded at one point only.

When acquiring vibration signals directly in digital form, one should sample at an appropriate frequency in order to obtain: (i) valid results when data is analyzed in the frequency domain, and (ii) accurate amplitudes of vibration signals in the time domain. To obtain valid results in the frequency domain, vibration signals while still in analog form should be passed through a low-pass filter with its cutoff frequency  $F_C$  set at least at the maximum frequency of interest. The appropriate sampling frequency  $F_s$  should be greater than  $(2 + 40/M) F_C$  where  $M$  is the attenuation rate of the low-pass filter. For accurate peak values of the time signal, the sampling frequency usually depends on the form of the transient signal and its predominant frequency. A sampling frequency equal to about 10 times the predominant frequency is normally sufficient.

Finally, calibration of individual components of the complete measurement system should be performed periodically in accordance with relevant standards and (or) recommendations by instrument manufacturers. In addition, end-to-end calibration of each channel of the complete system is recommended at the beginning and end of every vibration measurement session.

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