Vibration Transfer Mobility Measurements Using Maximum Length Sequences

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ABSTRACT
Vibration transfer mobility measurements are required under Federal Transit Administration guidelines when developing detailed predictions of ground-borne vibration for rail transit systems. These measurements typically use a large instrumented hammer to generate impulses in the soil. These impulses are measured by an array of accelerometers to characterize the transfer mobility of the ground in a localized area. While effective, these measurements often make use of heavy, custom-engineered equipment to produce the impulse signal. To obtain satisfactory signal-to-noise ratios, it is necessary to generate multiple impulses to generate an average value, but this process involves considerable physical labor in the field. To address these shortcomings, a transfer mobility measurement system utilizing a tactile transducer and maximum length sequences (MLS) was developed. This system uses lightweight off-the-shelf components to significantly reduce the weight and cost of the system. The use of MLS allows for adequate signal-to-noise ratio from the tactile transducer, while minimizing the length of the measurement. Tests of the MLS system show good agreement with the impulse-based method. The combination of the cost savings and reduced weight of this new system facilitates transfer mobility measurements that are less physically demanding, and more economical when compared with current methods.

1. INTRODUCTION
Detailed predictions of train vibration for environmental assessments require knowledge of the specific ground vibration propagation characteristics of the soil in the project area. A method to measure the soil propagation characteristics (“transfer mobility”) was developed by Nelson and Saurenman. This method has been adopted by the Federal Transit Administration (FTA) and the Federal Railroad Administration (FRA) for detailed analysis of train vibration.

The transfer mobility measurement as described in the FTA and FRA guidance manuals is illustrated in Figure 1: an instrumented hammer is used to generate an impulsive force into the ground, and the resulting vibration is measured at various locations near the point force using accelerometers or geophones. A transfer function is calculated from the measured force and vibration data using Fast Fourier Transform (FFT) techniques. The transfer function computation also generates a coherence function that can be used to verify the integrity of the measurement data. These data are then used to develop an estimate of vibration propagation over distance as a function of frequency.
Figure 1. Transfer mobility measurement schematic. Impulses generated by the instrumented hammer are measured by surface-mounted accelerometers to determine the transfer function.

2. CURRENT MEASUREMENT METHOD

Harris Miller Miller and Hanson Inc. (HMMH) currently uses custom hardware (referred to as the “winch/weight method”) to produce the required impulse. HMMH’s instrumented hammer consists of a 23 kilogram (50-pound) weight dropped on a load cell, as shown in Figure 2. An HMMH consultant, with assistance from a tripod-mounted power winch, uses a rope to lift the weight approximately 60 centimeters (two feet) above the ground. The consultant releases the rope and the weight falls onto the load cell to produce a 20,000-newton (4,500-pound) impulse into the ground. Similar methods are employed by various consulting firms around the world using electronic or pneumatic hammers.

Figure 2. Current HMMH instrumented hammer rig, consisting of a tripod-mounted mechanical winch powered by 12V car battery, 23-kg (50-lb) weight and load cell.

The relatively small amount of energy produced by a single-impulse results in a low signal-to-noise ratio. The signal-to-noise ratio increases by 3 dB for each doubling of the number of events. Therefore, the hammer drops are repeated at least 20 times at a single location to produce...
a reasonable signal to noise ratio. Up to a dozen impulse-measurement positions are used at each site to simulate the line-source effects of a train.

The vibration propagation testing procedure described above has been in use for over 15 years, and has proven to be adequate. However, the custom equipment used for this measurement has some significant drawbacks:

- Physically intensive process: The current method involves a large amount of physical effort to repeatedly lift/drop the weight up to 300 times per site, and to move the entire rig up to a dozen times per site. Considerably more effort is required to move the equipment in rugged terrain or in limited-access sites (subways for example). Data quality can be compromised as the operator tires and has difficulty producing “clean” impulses.
- Custom-fabricated components: The winch and weight components are custom manufactured. When parts break, new parts have to be manufactured by a local machine shop at a cost of several hundred dollars for each component. The project schedule may be affected if major repairs are needed.
- High costs: The current system typically requires at least two consultants to stabilize and operate the testing rig. In addition to the labor, the shipping costs for the vibration propagation rig can run up to several hundred dollars for ground shipping. The labor and shipping costs make it impractical to perform the transfer mobility testing for low-budget projects, or to perform supplemental vibration propagation tests for many large projects. Therefore, the consulting staff may have to perform vibration assessments using limited or no empirical data.

These drawbacks led us to design an implement and a new vibration measurement system based on Maximum Length Sequences (MLS) that would address each of these deficiencies. The goal of the system was to deliver the same, or better, data quality in the frequency range of 6 Hz to 200 Hz, while reducing physical labor and equipment costs.

3. MLS VIBRATION MEASUREMENT METHOD

A maximum-length sequence is a pseudo-random binary sequence that produces a high-energy impulse under circular autocorrelation. In essence, a MLS is a sequence of small impulses that, when processed with the correct autocorrelation or cross-correlation techniques, is equivalent to a large impulse. The impulse response of a system can be determined by introducing an MLS into the system (using the appropriate transducer), and then cross-correlating the system output with the original MLS. Figure 3 shows a sample MLS signal and the result of auto-correlating the same signal.
The impulse that is generated by the cross-correlation of the MLS input and system output is the impulse response of the system under test. Any noise that enters the system is represented as spurious responses in the tail of the impulse response. By applying an appropriate FFT window, most of the measurement noise can be excluded from the analysis. Rife and Vanderkooy\textsuperscript{5} define a MLS coherence function that can be used to verify the data integrity in a manner similar to using a traditional coherence function.

MLS signals have two important characteristics that are described in the literature\textsuperscript{5,6,7,8} and are summarized below:

- MLS signals have much higher energy than impulses, resulting in a very high signal-to-noise ratio. An MLS provides $L + 1$ times the signal power of an impulse, given the same peak amplitude, where $L$ is the length of the MLS in samples.
- MLS measurements have high distortion immunity, given a sufficiently long MLS period. Therefore, using an MLS of appropriate length can minimize non-linear distortions produced by a transducer. The high noise and distortion immunity characteristics of MLS allow the collection of high-quality data in noisy acoustic environments.

To minimize the cost of the system, a tactile transducer was selected as the vibration source. A tactile transducer is an electromechanical device similar to a loudspeaker that is designed to produce physical movement of a solid surface rather than creating pressure waves in the air. Tactile transducers are designed to produce low-frequency vibrations, and are often used to complement or replace subwoofers in consumer and professional audio systems. However, tactile transducers are also used in commercial, military, and even research applications. For example, tactile transducers are currently in use in Walt Disney Corporation and Universal Studios theme parks. The military uses tactile transducers in tank and helicopter simulators to provide a realistic training environment. A Stanford University graduate student used tactile transducers to generate ground-borne vibrations for post-doctoral research.\textsuperscript{9}
The MLS shaker system uses the “Buttkicker LFE” tactile transducer manufactured by the Guitammer Company Inc. as pictured in Figure 4. This transducer is available for under $300 at mail-order outlets and retailers around the world. The Buttkicker LFE is capable of producing a maximum force of several hundred newtons. The manufacturer claims that individual units are phased-matched\(^\text{10}\) so that, theoretically, two or more units could be used simultaneously to increase the maximum force amplitude. Our testing has shown that the Buttkicker can operate continuously for at least 10 minutes under a 500 watt load without showing significant thermal compression effects. The tactile transducer is calibrated using a commercially-available load cell.

![Tactile transducer mounted on load cell.](image)

A high-quality car audio amplifier is used to drive the tactile transducer. A car audio amplifier was chosen because car audio amplifiers are generally designed to deliver high power into low-impedance loads. Car audio amplifiers are also designed to operate under difficult conditions that might be encountered inside an automobile, such as extreme temperatures. The amplifier is powered by an automotive 12-volt battery, and is easily moved from site to site. A laptop computer equipped with a digital acquisition (DAQ) card is used to generate the MLS signal on site. The total shaker system (transducer, load cell, amplifier and battery) weighs less than 23 kilogram (50 pounds), compared with a weight of well over 40 kilograms (100 pounds) for the current winch/weight system.

4. MLS MEASUREMENT RESULTS

The MLS/shaker system was tested alongside the current winch/weight method to determine the effectiveness of the MLS technique. The winch/weight system was used to measure point source transfer mobilities at 11 locations according to standard HMMH measurement procedures. The MLS/shaker system was placed in the same locations as the hammer impacts. An array of six surface-mounted accelerometers was used to measure the ground vibration produced by both excitation sources. A schematic of the measurement layout is shown in Figure 5. A 65535-point MLS signal at a sampling rate of 1000 Hz was used to excite the tactile transducer. Each MLS measurement period lasted two minutes and 12 seconds (including one “warm-up” MLS run). The audio amplifier used for the measurement had a 200 Hz low-pass filter with a slope of 24 dB per octave.
Figure 5. Typical measurement layout (plan view). Excitation source is placed on “X” positions to simulate line source. Accelerometers measure ground vibration at “O” positions.

For these tests, the tactile transducer was calibrated by mounting it to a load cell and generating a white noise signal to measure the transducer’s frequency response. The calibration data was later used to normalize the measured transfer mobility based on the response of transducer. The transducer was than attached to a piece of wood measuring approximately 25 centimeters by 60 centimeters that was placed on the ground. Because the transducer can output a considerable amount of force, it has a tendency to lift itself off the ground under normal operation if not secured properly. Therefore, a consultant stood on the wood plank for each measurement to keep the transducer anchored to the ground.

Figure 6 shows a comparison of results obtained using the two measurement methods over the slant distances shown in Figure 5. The data presented in Figure 6 represent the shortest and longest distances typically used to collect transfer mobility data to show the best and worst case performances of the MLS method. The results given below are given as relative quantities, and have not been calibrated to their absolute values. However, these results are useful in demonstrating the effectiveness of the MLS technique.

The MLS results in the range of 10 Hz to 100 Hz show excellent agreement with the results produced by the winch/weight method even at slant distances of nearly 52 meters (170 feet). The MLS values below 10 Hz exceed the values generated by the winch/weight method by as much as 20 dB at all positions. We believe these discrepancies are caused by the calibration method used for this test. The transducer was calibrated by attaching it to the load cell, and letting the combined assembly vibrate freely. The testing was performed with the transducer anchored to the ground using the body weight of the attending consultant. Our testing has shown that low-frequency vibration transmission through the ground is significantly enhanced by anchoring the transducer to the ground. Therefore, we believe that the anchoring the transducer to the ground
during the calibration would have changed the low-frequency calibration data enough to reduce or eliminate the low-frequency differences.

It should be noted that the “free-vibration” calibration method produces a result that is conservative in the low-frequency range, so vibration impact will not be underestimated if this method is used. However, the use of the free-vibration calibration method may result in overpredicting low-frequency vibration levels which, in turn, may lead to unnecessarily high mitigation costs.

Figure 6. Comparison of vibration transfer mobility measurement results generated by winch/weight method and MLS method.

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The MLS results in the high-frequency range are five to 20 dB lower than the results from the winch/weight method. The coherence data for the winch/weight method indicates that the high-frequency data was contaminated by noise. Thus, the lower high-frequency results given by the MLS method can be attributed to the high noise immunity of the MLS signal method.

5. CONCLUSION

The results indicate that MLS vibration measurement method is suitable for transfer mobility testing. Additional research is needed to account for the low-frequency discrepancies, discussed above, but we believe that more accurate data can be collected through better calibration methods. Because of the relatively low forces generated by the tactile transducer, this system may not be suitable for measuring transmission into very heavy structures such as a cut-and-cover subway structure or masonry building. It is possible that a very long MLS signal (5 minutes or more) or a grouping of multiple tactile transducers can generate a sufficient signal to noise ratio or high enough force to generate the necessary impulse response in these situations.

Our research has shown that a measurement system costing less than $1000 dollars and weighing less than 23 kilograms (50 pounds) can be used to collect nearly the same data as a system that is substantially heavier and more expensive. This system uses commercially available off-the-shelf hardware that should minimize downtime caused by equipment breakdowns. The noise immunity of MLS signals will reduce the potential for over-predicting vibration levels, which will lead to cost-savings by reducing unnecessary vibration mitigation. The MLS measurement system can help reduce the cost and inconvenience in making transfer mobility measurements which will help produce more cost-effective vibration analyses.

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