euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Building structural impact response to Train pass-by and to MLS excitation

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Abstract

As part of the ground-borne noise assessment for the extension of the "EOLE" railway line to the west of Paris toward La Défense, an estimation of the structural response of 1870's era buildings located above the tunnel during train pass-by is required.
The vibration level amplification factor from foundations to floors is measured using an electrodynamic shaker.
This paper aims to check the validity of a new measurement method using an MLS (Maximum Length Sequence) pseudo-random signal [1] to estimate the transfer functions of vibration transmission from foundations to floors.
Some case studies of transfer function measurements performed inside a Haussmann-style building using both MLS and train pass-by events are presented and compared. The strengths and limitations of the use of this measurement method inside an occupied building are discussed.

Keywords: Ground-borne noise, building vibration, Railway, MLS excitation.

1 Introduction

EOLE, the extension of the RER E railway line towards Paris-West, links Tournan/Chelles in the East and Mantes-la-Jolie in the West. The new railway consists of the construction of an 8 km single bore tunnel running at a depth of 25 to 50 m. The tunnel follows a 19th century boulevard with a typical Haussmann-era architecture. In such cases, ground-borne noise and vibration from train services might disturb occupants of buildings with deeply buried foundations.
For some specific buildings near the future tunnel, an estimation of the foundation-floor vibration transmission must be obtained to estimate future ground-borne noise levels inside the buildings.
This paper presents a new method for the measurement of the foundation-floor vibration transmission. This method is applicable in a dense urban traffic area, in the basement of dwellings or hotels without car access.

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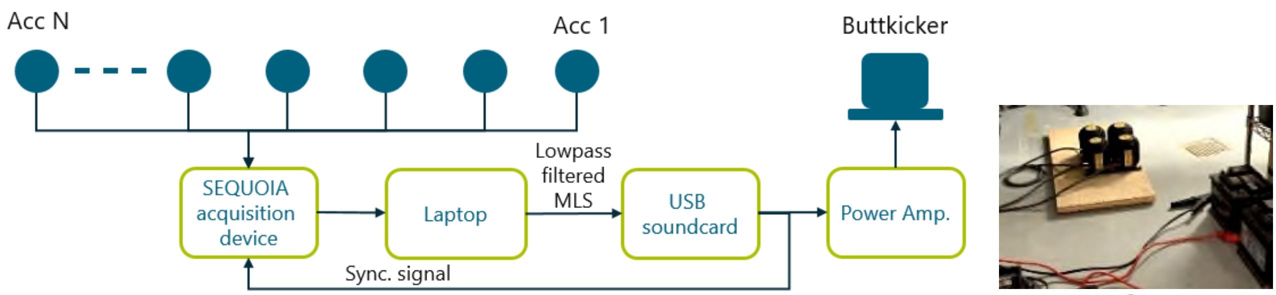
2 MLS vibration measurement system

The Maximum Length Sequence (MLS) method is widely used to measure impulse responses of acoustical spaces [2,3,4]. The source signal consists of a pseudo-random binary sequence generated using maximal linear feedback shift registers [1]. The impulse response can be derived directly from the cross-correlation between the MLS sequence and the measured output response as the MLS auto-correlation function is essentially an impulse [1]. When the MLS sequence is precisely repeated, the uncorrelated disturbances are reduced by synchronous averaging of the impulse responses, improving the signal-to-noise ratio (SNR) [4]. This critical advantage makes the method useful for measurements in noisy environments.

The MLS technique was selected to evaluate the vibration transmission in building structures. A tactile transducer is used as the vibration source. Figure 1 shows the overall schematic of the MLS measurement system and the tactile transducer: The Fischer Amps Buttkicker. Soil measurement tests with a similar MLS source were conducted by G. Coquel [6].



(a) (b)

Figure 1 : Schematic of the MLS measurement system (a) and the Buttkicker exciter (b).

The MLS measurement system uses a laptop computer to send MLS signal to 4 Buttkickers through a USB soundcard. The amplifier is powered by two 12V battery. During the measurements, the MLS signal is also sent to the acquisition device to allow perfect synchronization between the source and the receivers and hence precise impulse response reconstruction. The measurements are carried out using 16^{th} order sequences repeated 64 times, resulting approximately in a 2-minute signal (sampled at 32 kHz). The obtained 64 impulse responses are averaged to increase the signal-to-noise ratio. Thus, an averaged impulse response for each receiver position is obtained out of each 2-minute MLS acquisition.

To maximize the MLS signal amplitude, the sequence is low pass filtered with a lowpass Butterworth filter (fc = 150 Hz, order 4) so that the power amplifier amplifies only useful frequency content. The amplification gain is carefully controlled to avoid saturation of the Buttkicker exciter. Finally, four Buttkickers exciters connected in parallel and mounted on a plate are used to measure the vibration transmission in the building to further maximize the signal amplitude (power output 4x1000W RMS). The plate is placed on the ground in foundations and loaded with a weight of 160 kg.

3 Vibration measurements

The MLS measurement system, which is described in the previous section, was used to characterise the vibration transmission in a Haussmann-style building of seven floors located close to a railway tunnel. The building is located on the paved road “boulevard Haussmann”. Field measurements of vibration levels of the building foundations and the mid-span of floors were conducted. The MLS excitation source was placed on the second underground level. Five MLS sequences were used to excite the four tactile transducers. Each MLS sequence lasted two minutes as mentioned in Section 2. An array of seven tri-axle accelerometers was used to measure the produced vibration signals at a sampling rate of 1024 Hz. Acquired signals are upsampled from 1024 Hz to 32 kHz in order to correspond to the sampling frequency of MLS sequences. Two accelerometers were placed on the second underground level near the corner of the building for the foundations, and five accelerometers were placed at the mid-span of floor 2 (two sensors), floor 3, floor 4, floor 5 (i.e. no accelerometer on the ground floor).

Vertical vibration velocity level spectra are obtained by integration from the acceleration spectra measured using MLS excitations (the values obtained per third octave are divided by 2πf). The difference of velocity level spectra between each floor and the foundations is then calculated to determine the foundations to floor transfer functions.

The building under study is located close to a railway tunnel, a second vibration measurement has been carried out during train pass-bys at the same location as the MLS excitation. The foundations to floor transfer functions are calculated again from the train measurement.

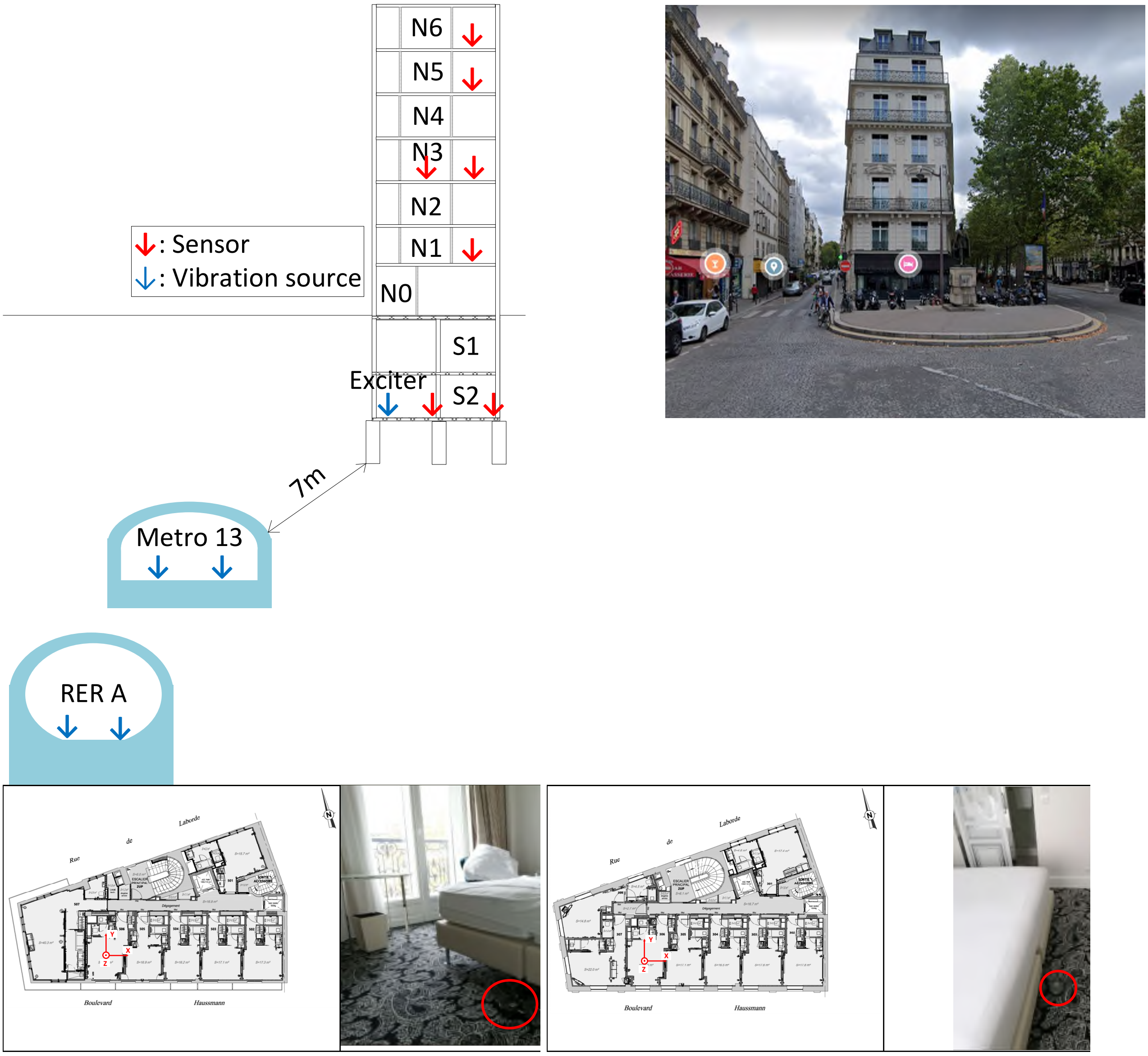
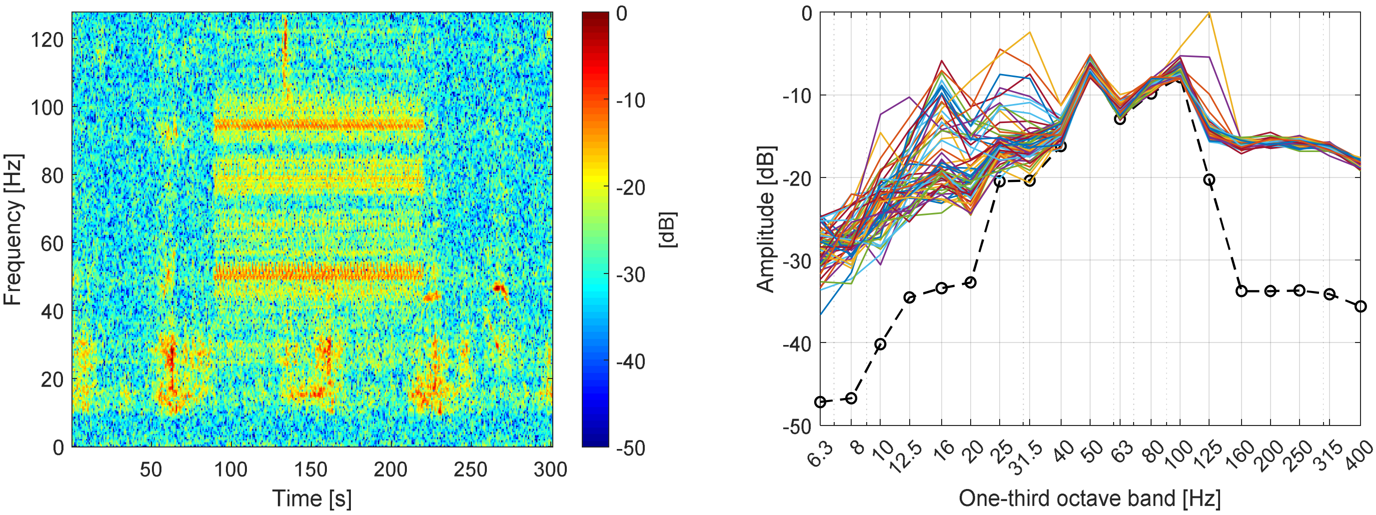


Figure 2 : Cross section and location of measurements floor 3 (left) and floor 5 (right)

4 MLS measurement results

Five 2-minute MLS sequences were used to excite the building from its second underground level. As an illustration, Figure 3(a) shows the spectrogram of the acceleration signal, sampled at 1024 Hz, measured on the 5th floor in response to a 2-minute MLS sequence. The deconvolution then extracts the 64 impulse responses and the average is calculated ignoring the first and the last responses, which may be singulars. The third octave band spectra of the 62 retained impulse responses and the spectrum of the average responses are plotted in Figure 3(b).



(a) (b)

Figure 3: (a) Spectrogram of the acceleration measured on the 5th floor in response to a 2-minute MLS sequence. (b) Spectra of the 62 associated impulse responses (coloured lines) and spectrum of the averaging over the 62 impulse responses (-o-).

On Figure 3(a), it is clearly seen that the exciter is on starting at 90 s from the beginning of the recording and then during 120 s. Furthermore, Figure 3(a) reveals a satisfactory signal-to-noise ratio between 40 Hz and 100 Hz. This indicates the excitation system's limitation for assessing the audible frequency range of ground-borne noise, as ISO TS 14837-31 specifies 4-250 Hz for the assessment of ground borne noise. However, impulsive noises are visible on the spectrogram below 40 Hz, and a low signal-to-noise ratio is observed. They are linked to train pass-bys as the building is located near a railway tunnel, as well as road traffic. This is also apparent in the 62 spectrums plotted (coloured lines) in Figure 3(b), which present a significant dispersion below 40 Hz, corresponding to frequencies of train-induced vibrations. The synchronously averaging over 62 successive impulse responses reduces extraneous noises, improving the signal-to-noise rate below 40 Hz and above 100 Hz (cf. Figure 3(b)). This result demonstrates the high noise immunity property of the MLS method [4].

Due to the high level of ambient vibrations in the building, an increase of the signal-to-noise rate was sought. The averaging is performed using five 2-minute MLS sequences, which makes it possible to treat 310 impulse responses (5 x 62 impulse responses of each MLS sequence). An averaged impulse response is obtained at each measurement location, and the associated spectrum is calculated in third-octave bands. Finally, the foundations to floor transfer functions are obtained from the third-octave spectra. These functions will be presented and discussed later in the paper.

5 Train measurement results

Located close to a railway tunnel, a second vibration measurement has been performed in order to evaluate the railway-induced ground-borne noise inside the building. A total of 46 train pass-bys (Metro Line 13 and RER A combined) was recorded with the same seven accelerometers placed at the same location as the MLS measurement described in previous sections. Two accelerometers are also placed at foundations, as stated above. Figure 4 shows the vertical averaged equivalent velocity level, calculated in third-octave frequency bands from the two measurements at foundations during 46 train pass-bys. The residual spectrums calculated for each sensor location between two train pass-bys are also plotted.

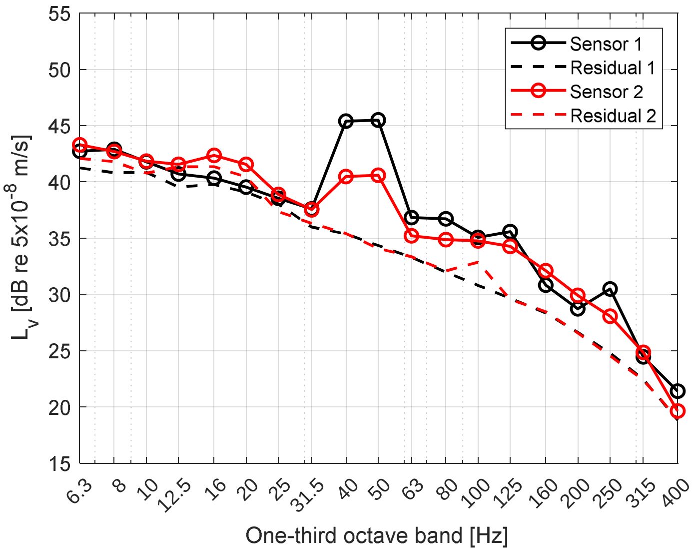
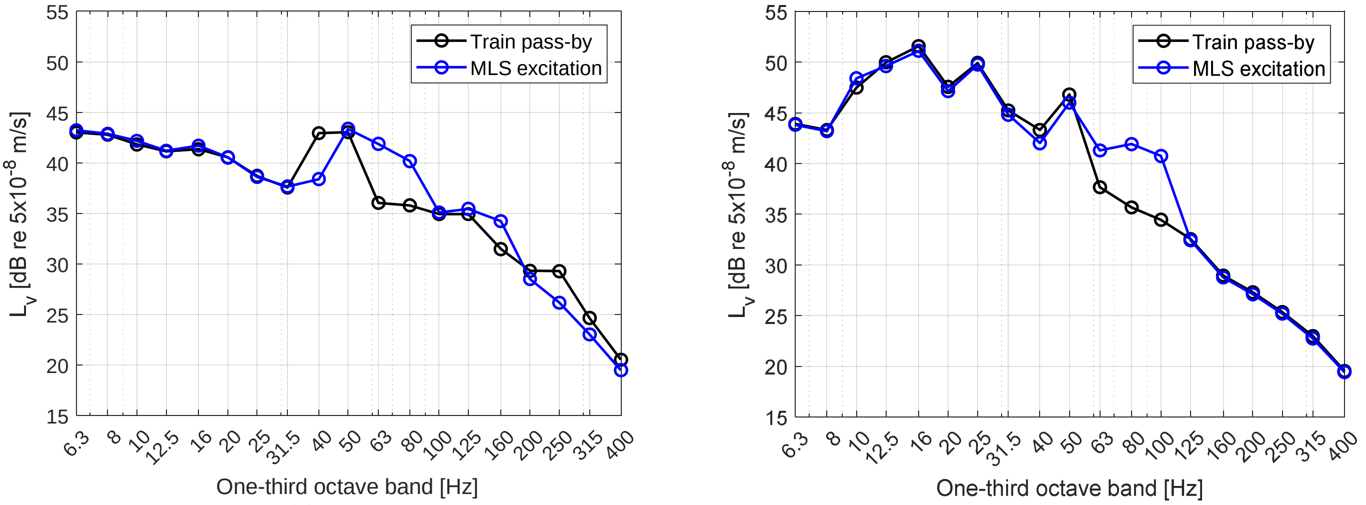


Figure 4: Vertical averaged equivalent velocity levels calculated from 2 measurements at foundations during 46 train pass-bys (-o-) and between pass-bys (---).

It is notable that the signal-to-noise rate is poor below 31.5 Hz. This is partly due to road traffic contributions as the building is also located near two very frequented paved roads.

The velocity levels induced by train pass-bys are now compared with those of MLS excitations. Figure 5 shows these levels averaged over 2 sensors at foundations and 2 sensors at floors. It can be stated that the MLS excitation frequency range is more extended than train excitation. The measured levels at floors during MLS excitation are about 5 dB above train pass-by excitation in the third-octave bands from 63 Hz to 100 Hz (cf. Figure 5(b)). The power of the exciter is insufficient to ensure a snr ratio greater than 5 dB in this building, an increase in the number of exciters and their power could improve the results



(a) (b)

Figure 5: (a) Vertical velocity levels induced by train pass-bys and MLS excitations averaged over 2 sensors at foundations (a) and floors (b).

6 Foundations to floor transfer functions

The foundations to floor transfer functions are calculated from both MLS and train pass-by measurements. The foundations to floor transfer functions are then calculated from the third-octave band spectra of the averaged impulse responses. It should be noted that 3 sensors showing an unsatisfactory signal-to-noise ratio due to unwanted disturbance were rejected. The two remaining measurements on floor 3 and floor 5 have the same resonant frequencies peak between 16 Hz and 25 Hz, typical for this Haussmann-style floors [5].
The average transfer function for floor 3 and floor 5 is plotted in Figure 6, as third-octave band spectra between 40 Hz and 100 Hz. Results out of this frequency range are not considered as the signal-to-noise ratio is unsatisfactory for MLS signal (cf. Figure 5).

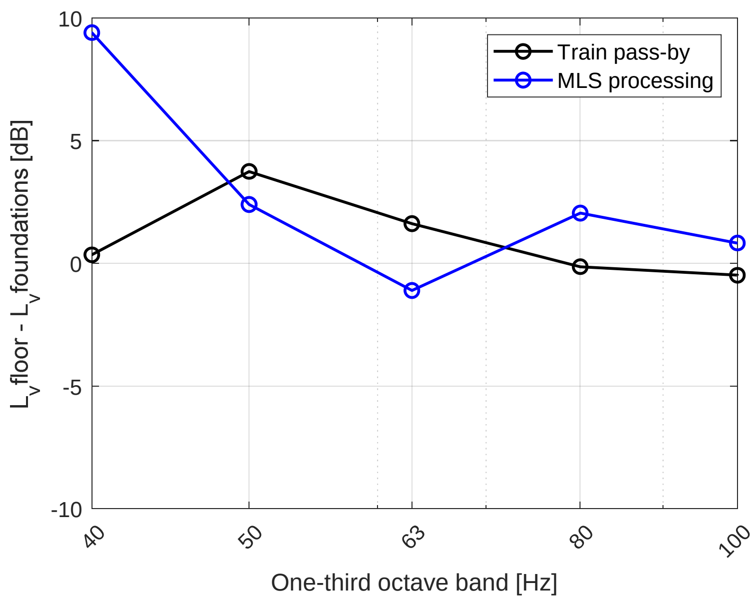


Figure 6: Foundations to floor transfer function for the building calculated from MLS and train pass-by measurements.

The curves show good agreement (less than 3dB difference) between the transfer function obtained from train pass-by and that from MLS processing in the frequency range from 50 to 100 Hz. However, the difference is more significant at 40 Hz and reaches about 10 dB. This difference at 40 Hz is observable Figure 5(a) at foundations, the MLS exciter does not manage to generate a vibratory level higher than the bottom level of the sensor.

7 Discussion

Differences between measured transfer functions : The measured transfer functions obtained from both vibration sources show good agreement except at 40 Hz. The difference between the transfer function obtained from train pass-by and that from MLS can be explained by the MLS transducer low frequency limitation. Indeed, the vertical velocity level difference at 40 Hz measured at foundations (Figure 5a) shows that the MLS transducer does not meet train pass-by levels. The velocity level measured during MLS excitation at floor 3 and 5 at 40 Hz is due to the train pass-by, in a building with quieter conditions it should be possible to measure lower in frequency with this exciter and more sensitive sensors.
Moreover the two vibrations sources are different : the train axles can be described as moving vibration sources on the tracks in tunnel, whereas the MLS transducer is applied in a single position at foundations.

Excitation signal : the chosen MLS signal is hard to reproduce with an electro-magnetic transducer because of its wideband frequency content. The magnitude of the power should be limited to avoid distortion, which leads to reducing signal-to-noise ratio. Using a sine sweep signal should lead to increase the signal-to-noise ratio for frequencies lower than 40 Hz. This is especially necessary in the case of Haussmann-like buildings with resonant floor frequencies around 25-35 Hz [5].

Immunity of MLS method to ambient vibrations : the human activities in the building, the local construction works, and the train pass-bys and heavy road vehicle pass-bys have to be rejected from the MLS measurements. Therefore, a series of 62 MLS sequences during 2 seconds each is used, the total MLS signal length is close to 2 minutes. The MLS method applied to this signal allows a rejection of up to -18 dB (=10*log(62)) of the noise uncorrelated with the MLS sequence in the upper (>125 Hz) and lower frequencies (< 40 Hz). This 2-minute or 62 MLS sequences signal seems acceeptable regarding to results measurements. Further averaging over 310 successive impulse responses shows a reduction of noise uncorrelated to MLS sequence up to 10*log10(310)= -25 dB. This higher number of averaging does not lead to better results in this building because of the low vibration levels at foundations below 31.5 Hz. Further measurements during the night period in the absence of unwanted vibrations could confirm the measurement results obtained during the day time.

Sensor sensitivity : the accelerometers sensitivity for these measurements is 1 V/g, which is a rather low value. The validity range of the MLS method could be much increased using more sensitive accelerometers (such as 10 V/g), especially for frequencies below 40 Hz. The use of the classic impact hammer was not retained due to the low sensitivity of the accelerometers and the difficulty to obtain an exploitable signal at low frequencies in a noisy urban environment.

Excitation location at foundations : the 4 MLS transducers (Buttkickers mounted on a plate) were placed at one single location at foundations which makes the measurements simple. The effect of moving this exciter at several excitation locations remains to be evaluated.

Transducer transportability : access to the building foundations is restricted because this level houses a spa. For this reason, a transducer of low weight and space is needed. Four transducers powered by two low-frequency amplifiers (12VDC) and one battery (12V 70Ah) was employed, for a total weight of 60 kg. the results obtained with the MLS signal show that the injected energy is insufficient outside the [40 Hz ;

100Hz] range. A higher power exciter is necessary to widen the exploitable frequency range for this type of measurements with an MLS signal.

8 Conclusions

A measurement method using MLS sequences for measuring the vibration frequency response of Haussmann-style buildings was developed. The measurement foundations and floor responses to the presented MLS excitation are compared to a railway excitation in a tunnel near the building. The validity range of this MLS method is nowadays limited to the one-third octave bands [50 Hz ; 100 Hz].
Using a higher power exciter or completing the MLS excitation by a sinus sweep to obtain the building response in the frequency range below 40 Hz should lead to increasing the signal-to-noise ratio [6].
Common vibrations sources used in similar projects are often construction machinery, which are not applicable in this case. The developed method is transportable, non-destructive, applicable in the basement of dwellings or hotels without car access.
The developed MLS method is suitable for MASW surface wave measurements [7] as well as buildings measurements for use in engineering studies.

Acknowledgements

The work presented in this paper has been carried out for SNCF within the framework of the extension of the RER E railway line, with support from CSTB.

References

[1] MacWilliams, F. J.; Sloane, N. J. Pseudo-random sequences and arrays. *Proceedings of the IEEE*, Vol 64 (12), 1976, pp 1715-1729.

[2] Schroeder, M. R. Integrated-impulse method measuring sound decay without using impulses. *The Journal of the Acoustical Society of America*, Vol 66 (2), 1979, pp 497-500.

[3] Rife, D. D.; Vanderkooy, J. (1989). Transfer-function measurement with maximum-length sequences. *Journal of the Audio Engineering Society*, Vol 37 (6), 1989, pp 419-444.

[4] Stan, G. B., Embrechts, J. J.; Archambeau, D. Comparison of different impulse response measurement techniques. *Journal of the Audio engineering society*, Vol 50 (4), 2002, pp 249-262.

[5] Walther, R., Suc, M., & Thoraval, E. Railway Induced Groundborne Noise And Vibration From Lines In Tunnel, Paris Rer E. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 2019, Vol. 259, No. 6, pp. 3284-3291.

[6] Guidorzi, P., Barbaresi, L., D'Orazio, D., & Garai, M. Impulse responses measured with MLS or Swept-Sine signals applied to architectural acoustics: an in-depth analysis of the two methods and some case studies of measurements inside theaters. *Energy Procedia*, Vol 78, 2015, pp 1611-1616.

[7] Coquel, G. & Kengang, A., Experimental Comparison of Maximum Length Sequence (MLS) and Impact Hammer Methods to Evaluate Vibration Transfer Functions in Soil. Notes on Numerical Fluid Mechanics and Multidisciplinary Design. 126, 2015, pp 149-156.