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BUILDING STRUCTURAL RESPONSE TO SINE SWEEP AND MAXIMUM LENGTH SEQUENCE EXCITATION

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ABSTRACT

ACOUSTB has proposed a method for measuring vibration levels generated in a newly constructed apartment building near a railroad line in Beaumont, France. The method involves using a portable transducer to measure vibrations and comparing them to train events. The aim is to estimate a transfer function associated with the transmission of vibrations from the ground to the building's foundations and to its floors. An electrodynamic vibrator placed outside is used to measure the amplification factor of the ground-to-floor vibration transmission. The objective of this work is to verify the validity of a new measurement method using two types of signals: a sine sweep and a pseudo-random MLS (Maximum Length Sequence) signal. A case study is presented, in which transfer function measurements are performed inside the building using both the proposed signals and the train events. The strengths and limitations of each measurement method are discussed. This study is important for validating the effectiveness of the proposed measurement method and for identifying improvement needs.

Keywords: *ground-borne noise, railway vibrations, MLS and sine sweep signals.*

1. INTRODUCTION

Railway ground noise is becoming a growing concern in urban areas due to the increasing use of rail transportation. The noise produced by trains and tracks can have a negative impact on the well-being of people who live near railway lines, affecting their sleep quality, causing annoyance, and potentially leading to health problems such as hypertension and cardiovascular disease [1]. Therefore, it is crucial to research and comprehend the effects of railway ground noise to develop effective mitigation strategies. To assess the impact of railway ground noise, it is necessary to calculate several transfer functions, which describe how the vibration is transmitted to building structures.

This paper introduces a new approach for measuring the transmission of vibrations in buildings. The method proposed in this study is designed to overcome the challenges posed by these types of environments and provide accurate measurements of ground-floor vibration transmission. More specifically, this study focuses on the excitation source signal utilized during the characterization process for measuring the transmission of vibrations. The objective is to compare the performance of the system, using two types of signal: the Sine Sweep [2, 3] and the Maximum Length Sequence (MLS) [4]. The MLS signal has already been used in a previous study [5] where the properties of MLS are utilized. In this article, we focus on the sine sweep signal.

2. OVERVIEW OF THE VIBRATION SYSTEM

MLS (Maximum Length Sequence) signals and Sine Sweep signals are two types of signals commonly used in acoustics and audio engineering for measuring system responses. They differ in their frequency content, amplitude, linearity, signal-to-noise ratio, dynamic range, and applications. MLS signals typically have a broad frequency range and a relatively constant amplitude, while Sine Sweep signals cover a narrow frequency range that changes over time and may have a varying amplitude.

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In this paper, the evaluation of vibration transmission in building structures was conducted using the Sine Sweep and MLS techniques, with a transducer serving as the vibration source. Similar systems have been used by [6, 7] to conduct soil measurements. An overall schematic of the measurement system and the Fischer Amps Buttkicker, which was used as the tactile transducer, is presented in Figure 1.

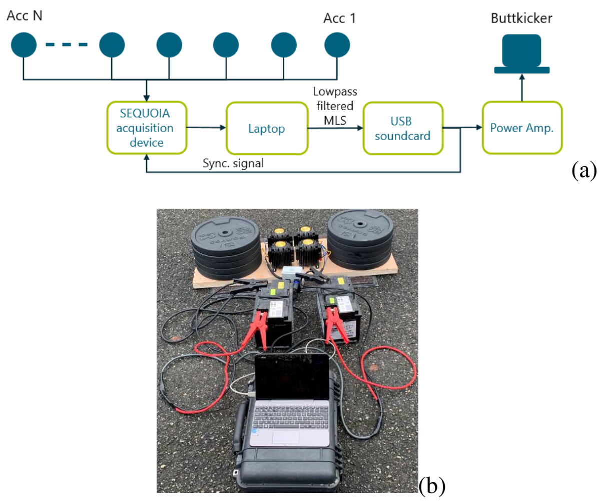

Figure 1. Schematic of the measurement system (a) and a photograph of the developed system (b).

To measure the vibration transmission on the building, the system employs a laptop computer to transmit the source signal to four Buttkicker units through a USB soundcard. The amplifier is powered by two 12V batteries. In order to ensure perfect synchronization between the source and the receivers, the source signal is also sent to the acquisition device during the measurements. To increase the signal amplitude and maximize power output (4x1000W RMS), four Buttkicker exciters are connected in parallel and mounted on a plate. The plate is loaded with a weight of 200 kg and placed on the ground surface, as depicted in Figure 1(b).

Figure 2 presents the spectrogram of the source signal used for the measurements, which involves two signal types. The first signal type is an Exponential Sine Sweep that ranges from 10 Hz to 80 Hz and lasts for 20 seconds. The Sine Sweep signal is sampled at 32 kHz and repeated 4 times with a 2-seconds silent period between each repetition. The second signal type consists of 16th order MLS sequences, which are repeated 30 times to create a signal duration of approximately 1 minute (sampled at 32 kHz). To ensure maximum MLS signal amplitude, the sequence is subjected to a lowpass Butterworth filter (fc = 150 Hz, order 4) to filter out any unwanted frequency content and allow the power amplifier to only amplify the useful frequency content. The amplification gain is carefully controlled to prevent the Buttkicker exciter from reaching high saturation levels.

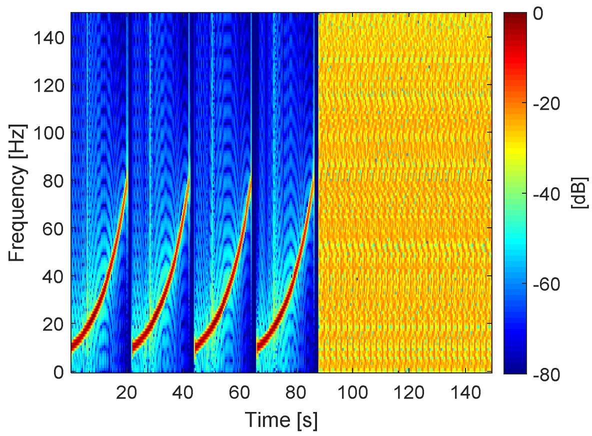

Figure 2. Spectrogram of the source signal of the measurement system. figure

3. VIBRATION MEASUREMENTS

The ISO/TS 14837-31 standard was used as a basis for establishing the measurement protocol [8].
The measurement system, which is described in the previous section, was employed to analyze the vibration transmission inside a 4-floors concrete building situated in the proximity of a railway line (distance of 12 meters between the building and the track). Field measurements were carried out to assess the vibration levels of the ground, building foundations, and the mid-span of the ground floor. The vibrator was positioned outside at 7m from the facade, and multiple sequences of the signal source were used. Each sequence had a duration of around 150 seconds, as explained in Section 2.

To measure the generated vibration signals, an array of three tri-axle accelerometers was utilized at a sampling rate of 1024 Hz. The acquired signals were upsampled from 1024 Hz to 32 kHz to match the sampling

frequency of the signal source and enable synchronization between them. Four accelerometers were placed outside, one accelerometer was placed on the underground level near the corner of the building foundations, and one accelerometer was positioned at the mid-span of the ground floor.
The velocity level spectra of vertical vibrations were obtained by integrating the measured acceleration spectra using MLS excitations (the obtained third-octave values were divided by 2πf). The transfer functions between the foundations and the floor, and the ground and the foundations were then calculated by subtracting the velocity level spectra of the ground floor from the foundations and the ground from the foundations, respectively.The building being studied is located in close proximity to a railway line (distance from building to rail of 12 m); therefore, the vibration measurements were also carried out during train pass-bys at the same location as the Sweep/MLS excitation. The transfer functions between the foundations and the floor, and the ground and the foundations were recalculated from the train measurement.

4. MEASUREMENT RESULTS

The building response to outside excitation using multiple Sweep/MLS sequences at various positions was measured. The acceleration signal, which was sampled at 1024 Hz and measured on the ground floor in response to four signal source sequences including sine sweep and MLS is presented in Figure 3.
For the remainder of the article, the last Sweep/MLS sequence produced between 800 and 950 seconds is chosen. This sequence has less disturbances, therefore a more interesting signal-to-noise ratio. Two train pass-bys can also be seen on Figure 3, taking place approximately at 50 seconds and 1000 seconds.
In Figure 4, the vertical velocity level is displayed, which is computed in third-octave frequency bands from the measurement on the ground floor using the Sine Sweep signal and the MLS signal. The figure also displays the velocity spectrum of the two train pass-bys.

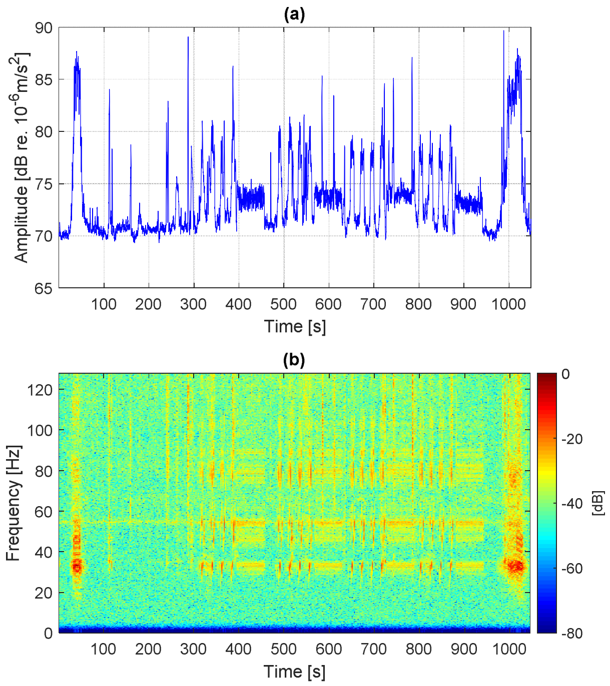

Figure 3. Time evolution of the 1-second moving average of the acceleration signal measured on the ground floor (a) and associated spectrogram (b).

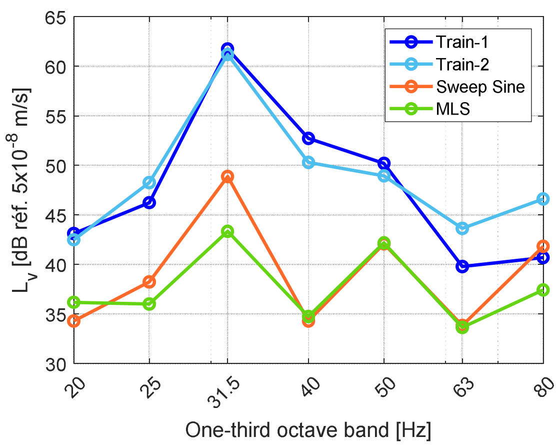

Figure 4. Vertical equivalent velocity levels from the measurement at the ground floor.

The two Lv spectra on the floor at the passage of the train and under artificial excitation show the same trend at 31.5 Hz and 50 Hz. We observe two gaps in the spectra due to the system itself (two emission gaps at 40 Hz and 60 Hz)

detailed in the following. The peak at 31.5 Hz corresponds to the first resonance mode of the concrete floor, dimensions 5 m by 6 m, thickness 20 cm.
The vibrator is placed at 7 m from the facade and facing the instrumented room. The train track is at a distance of 12 m from the facade. The Lv spectrum obtained with the artificial source is 10 dB to 15 dB below the train Lv spectrum between 20 Hz and 50 Hz, which is promising for its use to simulate a train passage in real conditions.
The comparison between the two types of signals shows a difference between the Lv spectrum obtained on the ground floor for Sine Sweep and MLS. The Sine Sweep gives +7 dB at the 31.5 Hz third octave band and +4 dB at the 80 Hz third octave band. For the others third octave bands, there is little difference between both signals.

This improvement in favor of the Sine Sweep has been observed in other studies for sound pressure sources (acoustic), an improvement of the sound pressure level order of +10 dB for all frequencies has been observed, which we do not find here. This phenomenon is related to the limitations of the vibrator, the response of the transducer not being ideal. The limits of the excitor are visible in the spectrograms Figure 3. The saturation and non-linearity of the exciter do not allow linear levels to be emitted over the frequency range of interest, particularly given the absence of emissions around 40 Hz and around 60 to 70 Hz.

5. TRANSFER FUNCTIONS

To evaluate the response of the building to a surface excitation (train, artificial source), it is necessary to estimate the soil-foundation attenuation, and the floor amplification. We present energy ratio measurements (transfer functions in dB) between ground and floors, and foundations and floors.

5.1 Foundations to floor transfer functions

The measured Foundations to floor transfer functions obtained from Sweep Sine, MLS and train pass-by are presented in Figure 6.

The foundation to ground-floor transfer function presents a floor resonance of +20 dB at 31.5 Hz with train excitation, this value is very important compared to measurements in other similar buildings, which can be explained by massive foundations and an absence of furniture.

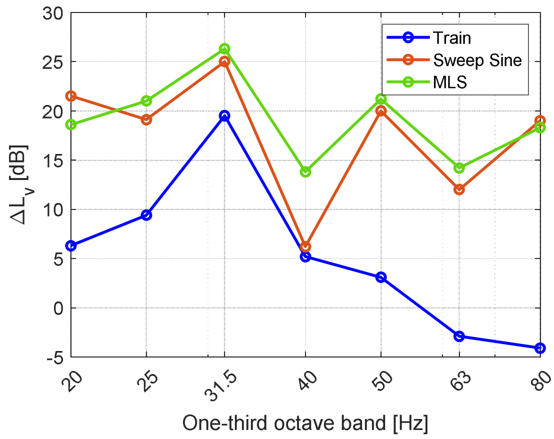

Figure 6. Foundations to floor transfer function for the building calculated from Sweep Sine, MLS and train pass-by measurements.

This resonance is correctly observed with our system, at 31.5 Hz a good agreement is found between train excitation and Sine Sweep or MLS excitation (+5 dB difference). However, for the third octave 40 Hz, 50 Hz and 63 Hz, a difference of +15 dB is observed between both Sine and MLS, and the train, which is not satisfactory. This can be explained by the type of excitation, our artificial point source placed outside the building injects little energy in the foundations of the building, unlike the train for the range 40 Hz to 63 Hz.

5.2 Ground to floor transfer functions

The measured ground to floor transfer functions obtained from Sweep Sine, MLS and train pass-by are presented in Figure 7. The floor first resonance at 31.5 Hz is observed, the room presents an amplification from ground to floor of +7 dB with train excitation, which is a typical value measured in similar constructions.
This resonance is correctly observed with our system, good agreement between train and sine (+4 dB of difference at 31.5 Hz). The agreement is weaker for MLS (+11 dB difference at 31.5 Hz).
For all the third octave between 20 Hz and 80 Hz, the agreement obtained is satisfactory for Sine (difference of about +5 dB below 40 Hz and about -5 dB between 50 Hz and 80 Hz).
In this arrangement of vibrator placed in front of the building and close to the railroad tracks, the results show the interest of this system with a Sine Sweep signal.

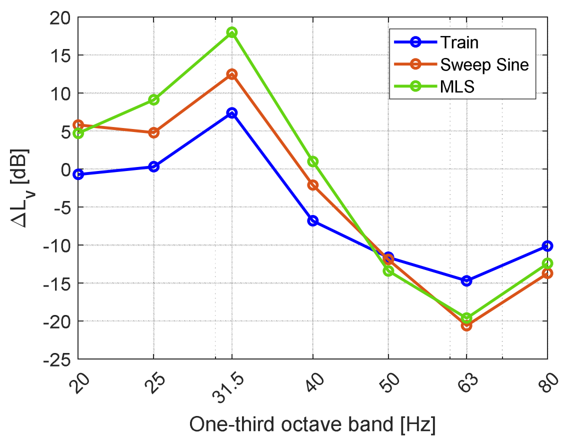

Figure 6. Ground to floor transfer function for the building calculated from Sweep Sine, MLS and train pass-by measurements.

6. DISCUSSION

The measurement is of interest to qualify the building vibration response including the propagation from the ground to the floor, with a carefully chosen position of source and sensors. A satisfactory agreement is obtained (5 dB difference) between transfer function measurements with the vibrator and train excitation.

The foundations to floor transfer function calculated from Sweep Sine shows a satisfactory agreement limited to the 31.5 Hz third octave band, compared to train excitation. For the third octaves 20 Hz to 25 Hz and 40 Hz to 80 Hz, the agreement is not satisfactory. Compared to train excitation, the velocity level spectra measured with vibrator excitation on foundations is very low. In this case, the vibrator is insufficient to simulate the train excitation. We do not recommend using this vibrator on the ground surface to estimate ground-foundation transfer function. One potential improvement could be to sum the contribution of multiple excitation points to simulate a linear source such as a train.

The ground to floor transfer function calculated from Sweep Sine shows a satisfactory agreement from 20 Hz to 80 Hz third octave band, compared to train excitation. It should be noted that the results obtained in the presented example require a specific positioning of the vibrator and sensors on the ground surface. It is interesting to note that despite the difference between the two sources (point source vibrator and linear source train), a usable transfer function for acoustic impact studies is obtained with a simple system.

Other vibration sources have been used for this type of measurements such as construction equipment. The advantage of this vibrator is its portability, as well as the possibility of performing advanced signal processing treatments. In situations of pre-existing exposure to vibrations (road traffic, construction work, activities within buildings), it is possible to perform advanced signal processing treatments to reject ambient disturbances. An improvement of the system including the measurement of the vibrator force is envisaged.

Emission gaps related to the transducer in certain frequency bands are observed. To improve the signal-to-noise ratio in these ranges for future studies, a modification of the signal and/or transducer is required, especially for the third octave band 40 Hz which is relevant in the vibration analysis of buildings.

7. CONCLUSION

The presented method is valid to obtain a transfer function associated with the transmission of vibrations from the ground to the building's foundations and to its floors.
Measurements of the ground vibration, foundations vibration and floor vibration are presented for the Sine Sweep and MLS signals and compared to train excitation.
The Sine Sweep is better adapted in this case than the MLS. Using a Sine Sweep signal, differences of about 5 dB compared to train excitation are observed depending on the transfer function studied.
The foundations to floor transfer function showed a satisfactory agreement limited to the 31.5 Hz third octave band, compared to train excitation.
The ground to floor transfer function showed satisfactory agreement extended from the 20 Hz to 80 Hz third octave bands, compared to train excitation.
This method is applicable to evaluate building transfer functions in the case of a railway project near an existent building (tramway or train).

For future studies, it is necessary to quantify the influence of the vibrator position and of the sensors positions on the ground.

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