

VIBRATION TRANSFER MOBILITY MEASUREMENTS COMBINING FALLING WEIGHT AND IMPACT HAMMER EXCITATION METHODS

Giovanni Farotto and Alexis Bigot

SIXENSE, Lyon 69 - France, +33 (0)4 72 69 01 28

giovanni.farotto@sixense-group.com

ABSTRACT

For construction in an urban environment, vibration transfer mobility measurements are useful when developing detailed prediction of ground-borne vibration and ground-borne noise for underground or surface rail transit systems. These measurements typically use a large impact hammer to generate impulses in the soil and an array of accelerometers or velocimeters to measure the vibration response to the impulses. The correlation between the force and the vibration results is used to characterize the transfer function of the ground in a localized area.

The effectiveness of this approach is limited by the amplitude of the force impulse when dealing with larger zones and SSI attenuation, especially for larger buildings, where a satisfactory signal-to-noise ratio cannot be achieved with traditional methods. In some of these cases, a seismic vibrator truck can be deployed on site, but site specific constraints do not always make this possible.

To address these shortcomings, a double stage measurement method has been developed by using a “weight drop” approach combined with the impact hammer.

The methodology that combines the processes of the two impulse-inducing methods and controls the uncertainty of the measurement chain is presented in this paper. The technique will be detailed and an application case on a shaft of the “Grand Paris Express” project will be presented with emphasis on the added value for the parties involved.

1 INTRODUCTION

Detailed predictions of railway 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 (1988). This method has been adopted by the Federal Transit Administration (FTA) (1995) and the Federal Railroad Administration (FRA) for detailed analysis of railway vibration. The transfer mobility measurement, as described in the FTA and FRA guidance, is carried out using a hammer to generate an impulsive force into the ground, of which the resulting vibration is measured at various locations near the point force using geophones.

A transfer function is calculated from the measured force and vibration data using Fast Fourier Transform (FFT) techniques. The transfer function calculation also generates a coherence function that can be used to verify the integrity of the recorded data. This data is then used to estimate the vibration propagation over distance as a function of frequency.

Some analysis methods such as the MLS vibration measurement method (Singleton Jr, 2005) are suitable for transfer mobility testing, but this system may not be suitable for measuring transmission into massive structures such as a cut-and-cover subway structure or masonry building.

Alternative methods have thus been developed for the purpose of this study.

2 CONTEXT

An exploratory shaft has been constructed in Saint-Cloud (France), where a metro station is to be constructed for the Grand Paris Express project in Paris.

Vibration transfer mobility measurements are being carried out to provide additional information for the model used to assess vibration impact of the construction works and the future metro line operation.

The distance between the exploratory shaft and sensitive receptors (hospital) is approximately 20 meters. The shaft and the hospital are on either sides of a street. Given the distance and the ambient vibration characteristics of the urban environment, it would be too difficult to carry out classic transfer mobility measurements with a traditional impact hammer.

Therefore, an alternative had to be sought and a combined mass / hammer method was developed to overcome the local restraints.

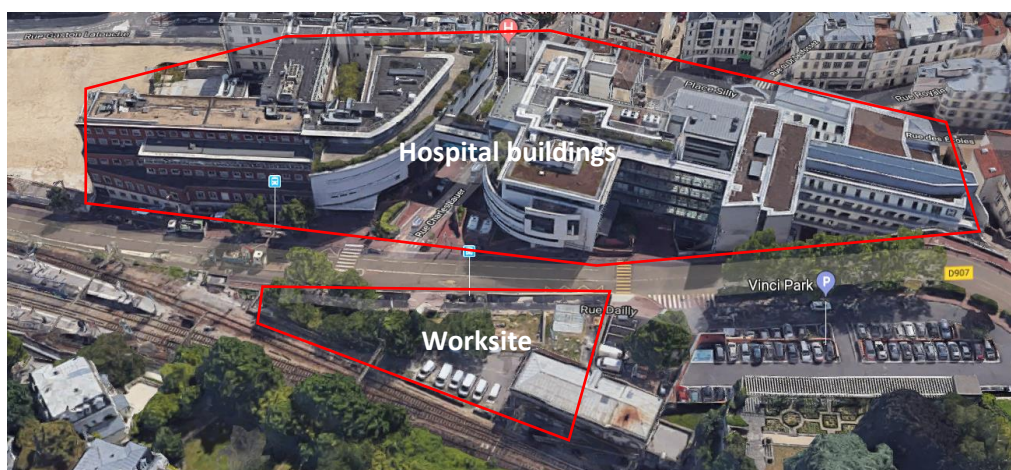


Figure 1: Aerial view of the worksite and sensitive buildings

3 MEASUREMENT METHODOLOGY

3.1 GENERAL PRINCIPLES

In order to measure the vibration response inside the sensitive buildings located on the other side of the road, the equipment chosen to induce the impulse in the ground is a 600 kg mass, falling from between 5 and 7 m high.

Since the impact force of the masses cannot be directly measured, an indirect approach was used and measurements were carried out at predefined reference points to establish the vibration responses of both the falling weight and impact hammer.

The force of the impact hammer was measured to determine the force of the falling mass.

The following pictures (Figure 1) show the installation of reference points (four sensors around the impact position) inside the exploratory shaft and the equipment used for the measurements.



Figure 1: Installation of reference points

3.2 SENSOR NETWORK

A network of vibration sensors was installed inside and outside sensitive buildings, as shown in the figure below. Sensors are tri-axial geophones (SYSCOM MR3000C), configured for continuous and synchronized vibration recording. The sensors have been installed inside the buildings on various floors.

For the purpose of this paper, we will focus on three measure points in particular (circled in the aerial view in the figure below), plus the reference point at the bottom of the shaft, as shown in the figure below. The other sensors are not relevant for this transfer mobility analysis and will be ignored.

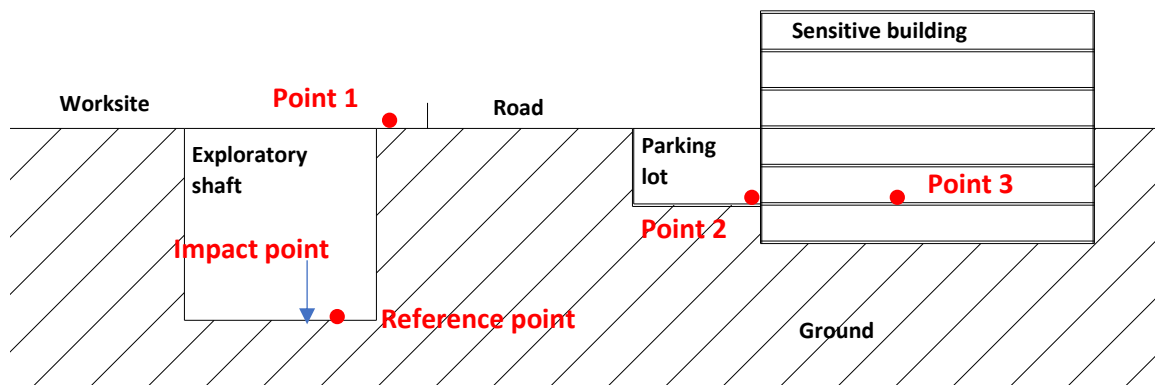
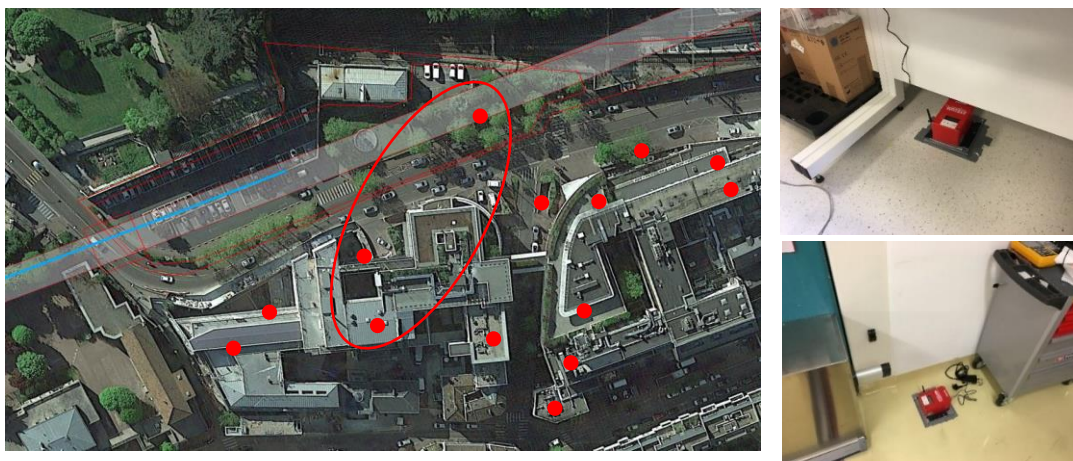


Figure 2: Sensors location

3.3 MEASUREMENT CONDITIONS

All sensors have been synchronized and installed with the same orientation (y-axis facing north).

The sensors inside the buildings were fixed to the floor using epoxy glue, while the sensors on the ground outside were fixed using metal spikes.

For the falling mass, a layer of sand was laid on the ground, to ensure some level of energy distribution over frequencies during the impact.

For the impact hammer, a metallic plate (200 x 200 x25 mm) was laid over the impact point in order to ensure wider shock distribution.

For improved repeatability, a series of at least 15 impacts were carried out for impact hammer tests and for falling weight tests. Each time, the falling height was set to approximately 7 m.

A set of four reference geophones were also deployed in four different directions, equidistantly around the impact point at the bottom of the shaft to account for heterogeneous soil response.

Other factors leading to measurement uncertainty due to technical constraints were:

- The geometrical precision of the point of impact of the falling weight, due to the difficulty of the weight drop installation inside the exploratory shaft.
- The background vibration, even though the test was carried out at night.

All measurements have been performed with a 1000 Hz sampling rate.

Results were given in 1/3 octave band within the 4 Hz – 315 Hz frequency range.

Each impact sample is set to 1-second duration for all measurements.

4 MEASUREMENT RESULTS REPEATABILITY AND PRECISION

In order to check the reliability of measurements in terms of repeatability and precision, two main controls were performed on each measurement: a coherence check and a background noise check.

For each velocity measurement, a control of signal over background noise was calculated by comparing the signal PSD (power spectral density) to the background noise PSD (background noise being the signal recorded by the sensor immediately after the impact response).

As for the impact mass measurements, the coherence function was calculated between the impact mass force and the velocity measured at each reference point.

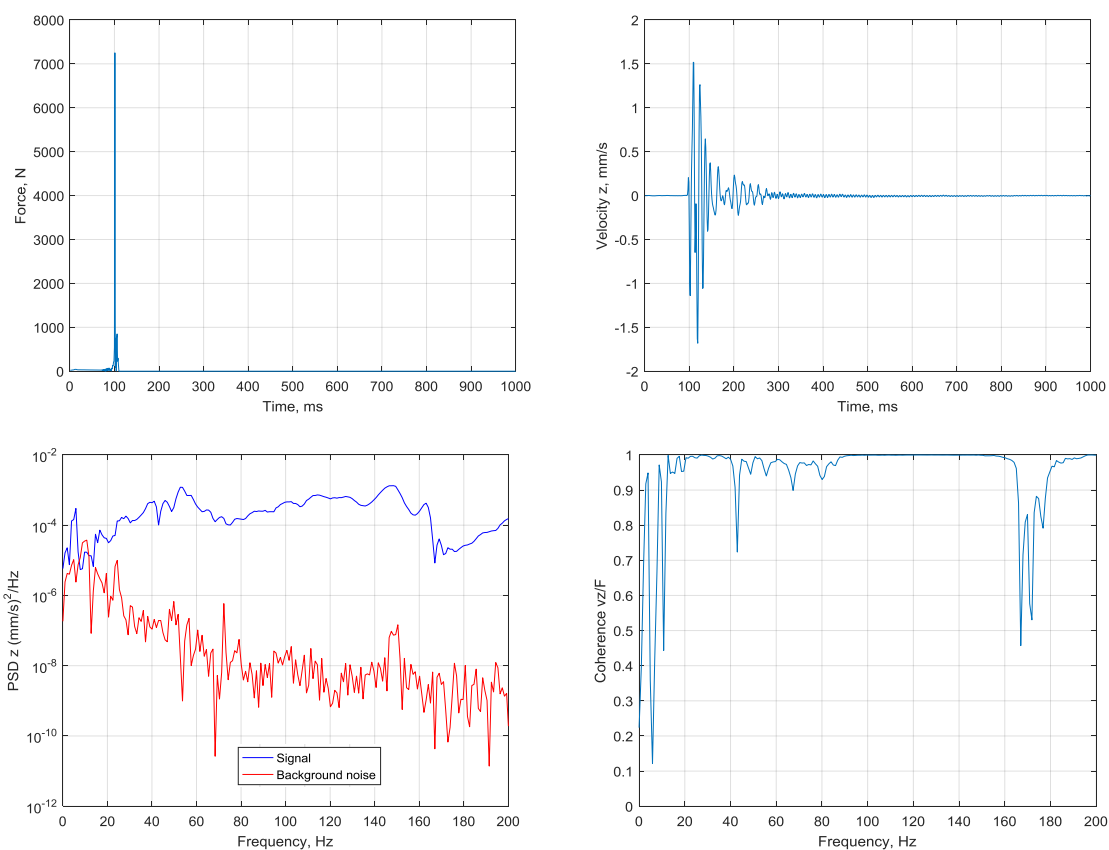


Figure 3: Falling weight measurement example.

(1) Force (2) Velocity at reference point on vertical axis (3) PSD on vertical axis (4) Coherence function (v/F)

For the falling weight measurements, the same function was calculated between the velocity measurements at the receiver point and each reference point.

An example of these calculations is shown below for the receiver point just outside the shaft (Point 1), on the surface.

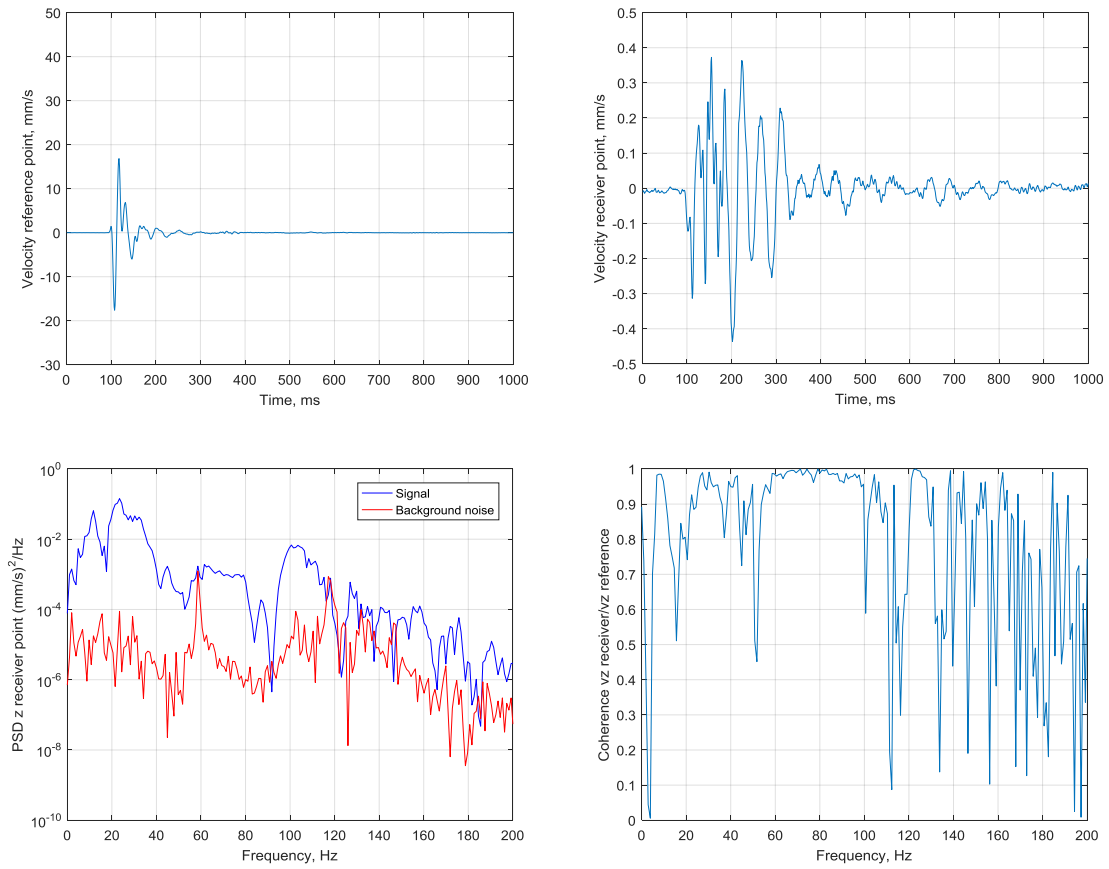


Figure 4: Coherence between a reference point and Point 1.

(1) Velocity at reference point (2) Velocity at receiver point (3) PSD on vertical axis (4) Coherence function (v/F)

Another set of results is given here for a receiver point just outside the nearest sensitive building (Point 2), on the base of one of the outer walls facing the worksite and the shaft.

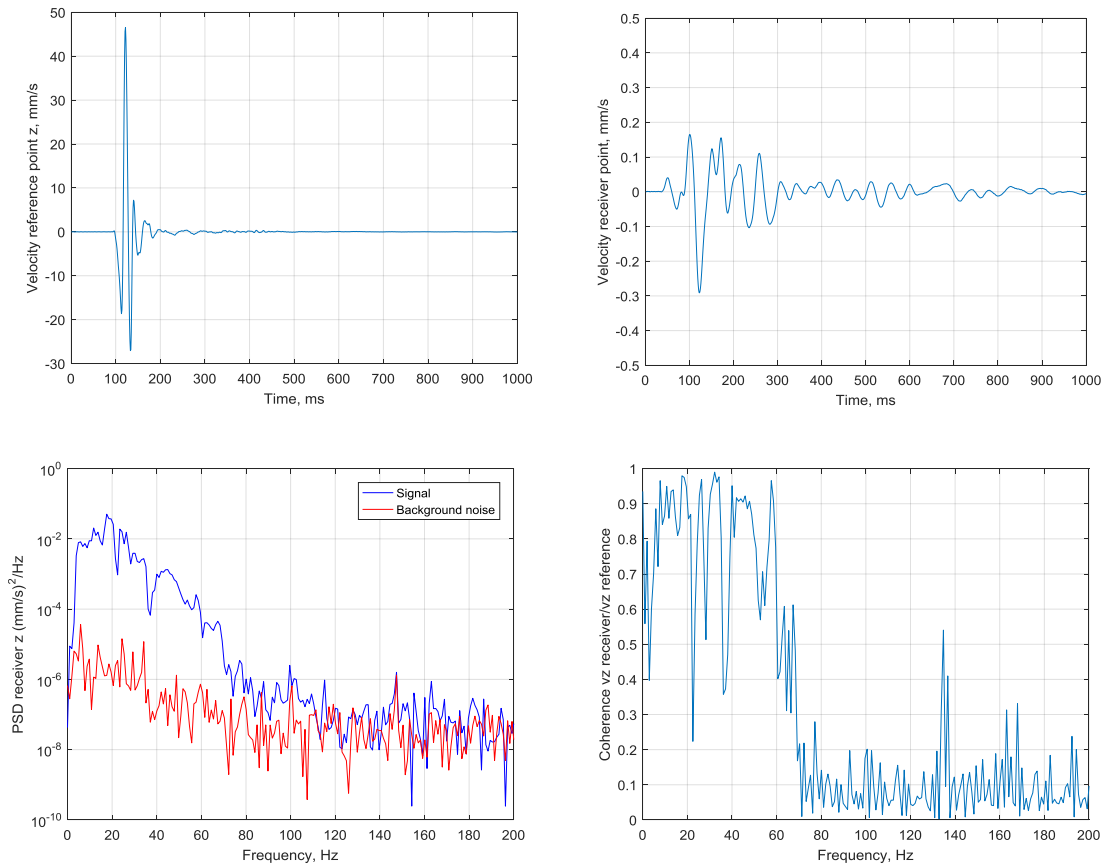


Figure 5: Coherence between a reference point and Point 2.

(1) Velocity at reference point (2) Velocity at receiver point (3) PSD on vertical axis (4) Coherence function (v/F)

The final example given below is for the receiver points inside the sensitive buildings (Point 3), approximately 40m from the impact point.

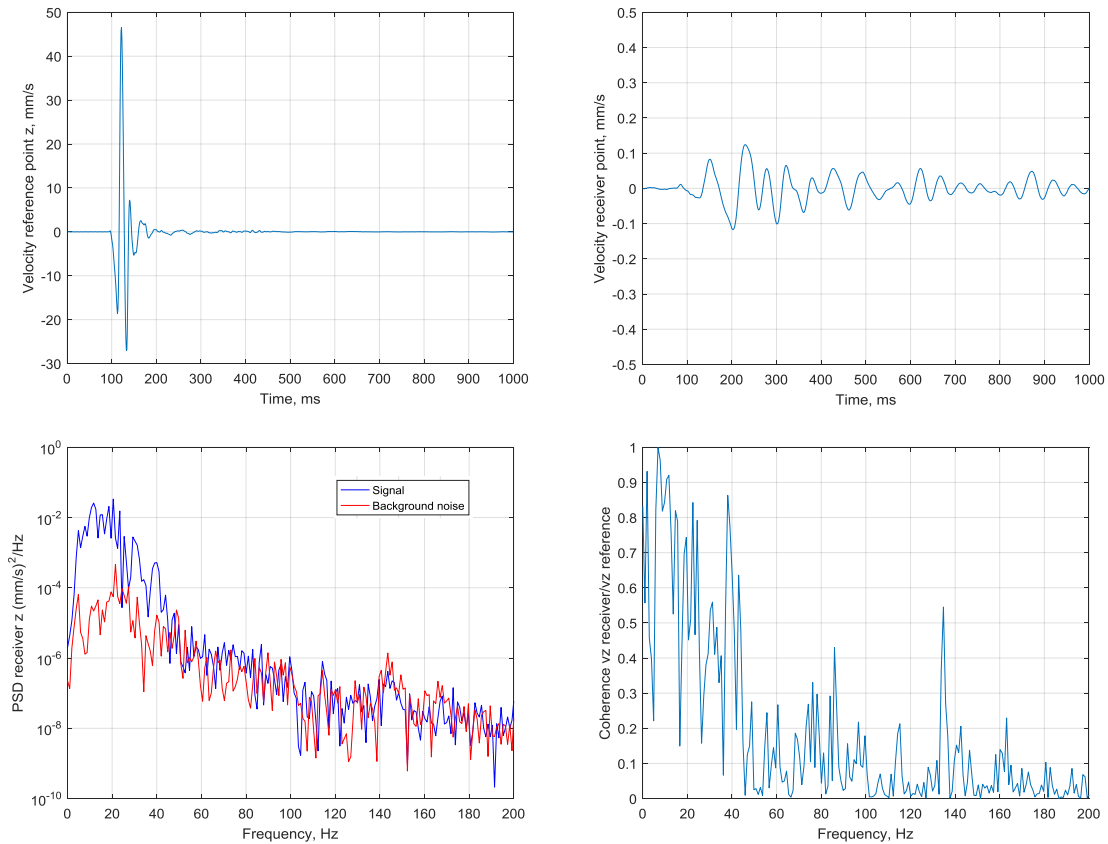


Figure 6: Coherence between a reference point and Point 3.

(1) Velocity at reference point (2) Velocity at receiver point (3) PSD on vertical axis (4) Coherence function (v/F)

Basic results remarks:

The comparison of the three sets of results shows that the energy of the falling weight is high enough to excite the building, but given the frequency response of the building itself and the background noise, the impact response at Point 3 is similar to the background noise for most of the frequency range over 50 Hz.

For the receiver point just outside the shaft (Point 1), the impact response is high enough compared to the background noise for most of the frequency range up to 200 Hz.

As for the receiver point halfway, on the outside wall of the building (Point 2), the impact response is higher than the background noise up to 120 Hz.

5 TRANSFER MOBILITY ANALYSIS

The analysis of the impact mass measurement results gives an indication of the local transfer mobility at the bottom of the shaft, between the reference point and the impact point. The calculation methodology applied (Verbraken, 2012) is the following:

$$\text{Transfer mobility} = L_{v \text{ ref}} - F_{\text{exc}} \text{ (vibration level – excitation force level)} \tag{1}$$

This transfer mobility is plotted below for all impact hammer tests. The black dashed curve gives the average values of the transfer mobility over all the realized tests in vibration decibel (dBV, reference $5 \cdot 10^{-8}$ m/s).

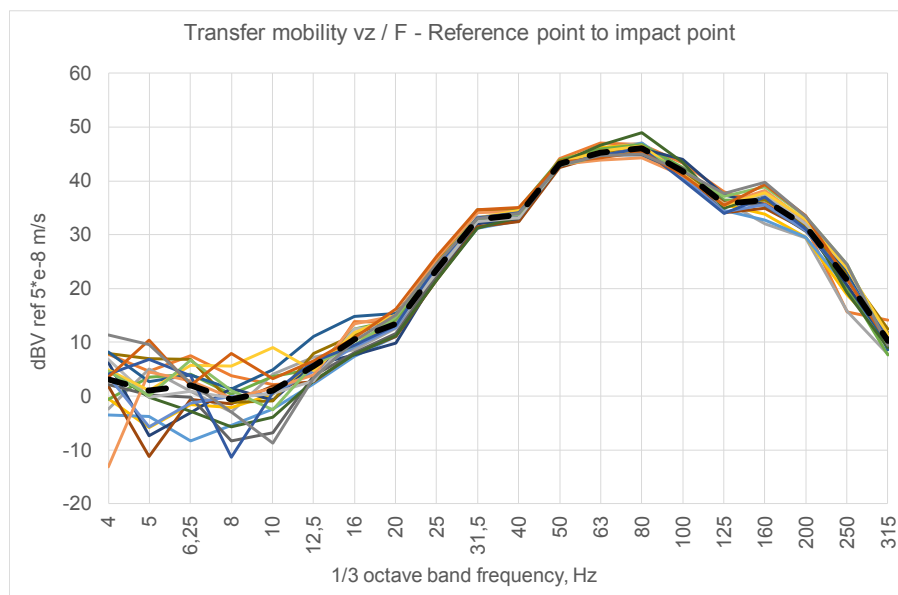


Figure 7: Transfer mobility vz/F – Reference point to impact point

As for the falling weight tests, by comparing the local transfer function and the vibration measurements at the reference point, we can estimate the falling weight impact force (F_{excW}).

$$F_{excW} = L_{v \text{ ref}} - \text{transfer mobility} \tag{2}$$

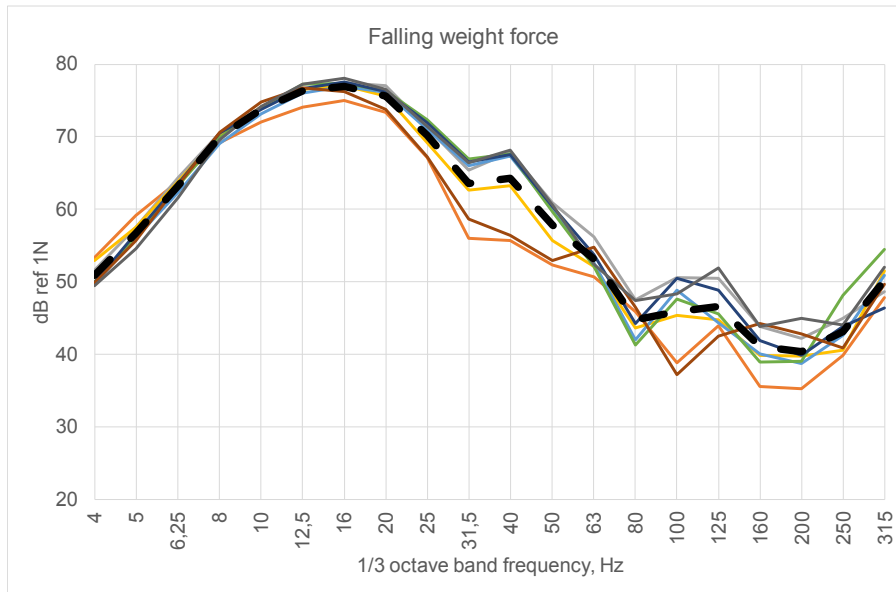


Figure 8: Falling weight force estimation

By applying the calculation methodology to measurement points located further away, we can estimate the transfer mobility for points 1, 2 and 3.

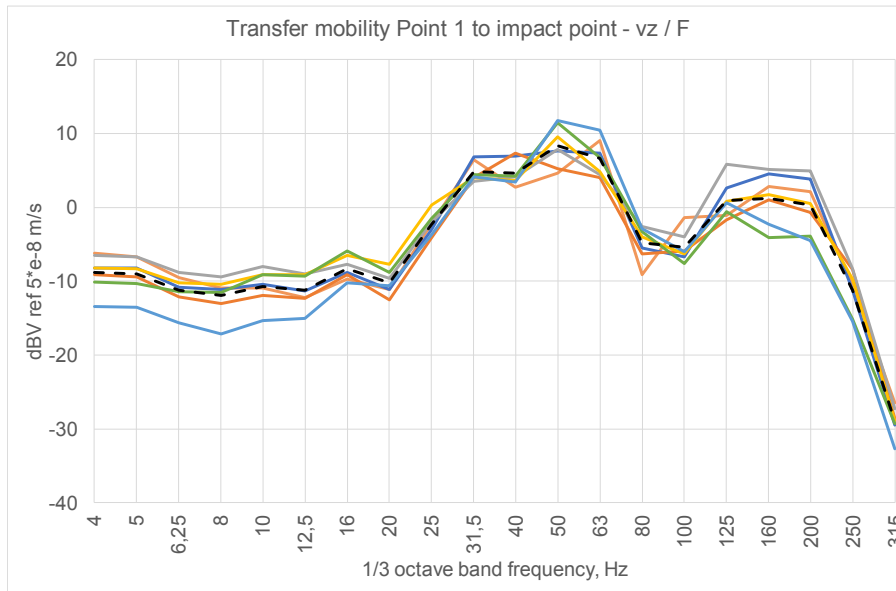


Figure 9: Transfer mobility vz/F – Point 1 to impact point

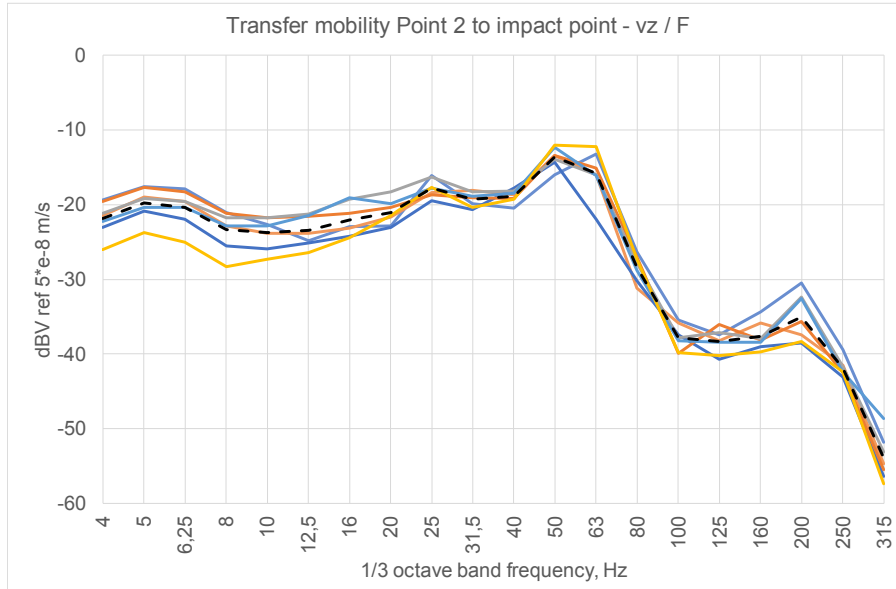


Figure 10: Transfer mobility v_z/F – Point 2 to impact point

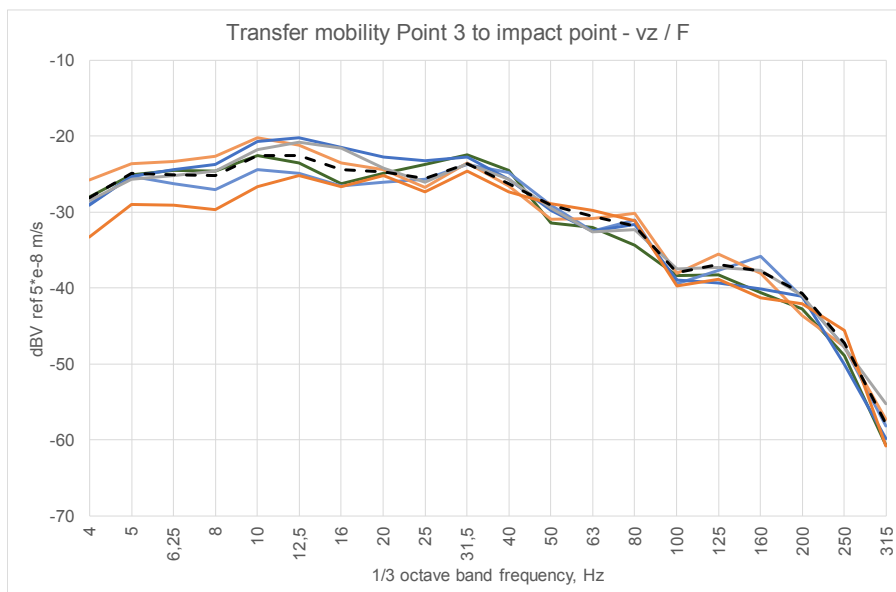


Figure 11: Transfer mobility v_z/F – Point 3 to impact point

For easier comparison, we overlay the average of each point transfer mobility on the same graph. This comparison shows the different kind of attenuation between the measurement points:

- A higher energy loss between points 1 and 2, due to the ground attenuation over distance between the two points and to the soil structure interaction.
- A lower energy loss between points 2 and 3, due to the building structural response between the outer wall and the receiver room.

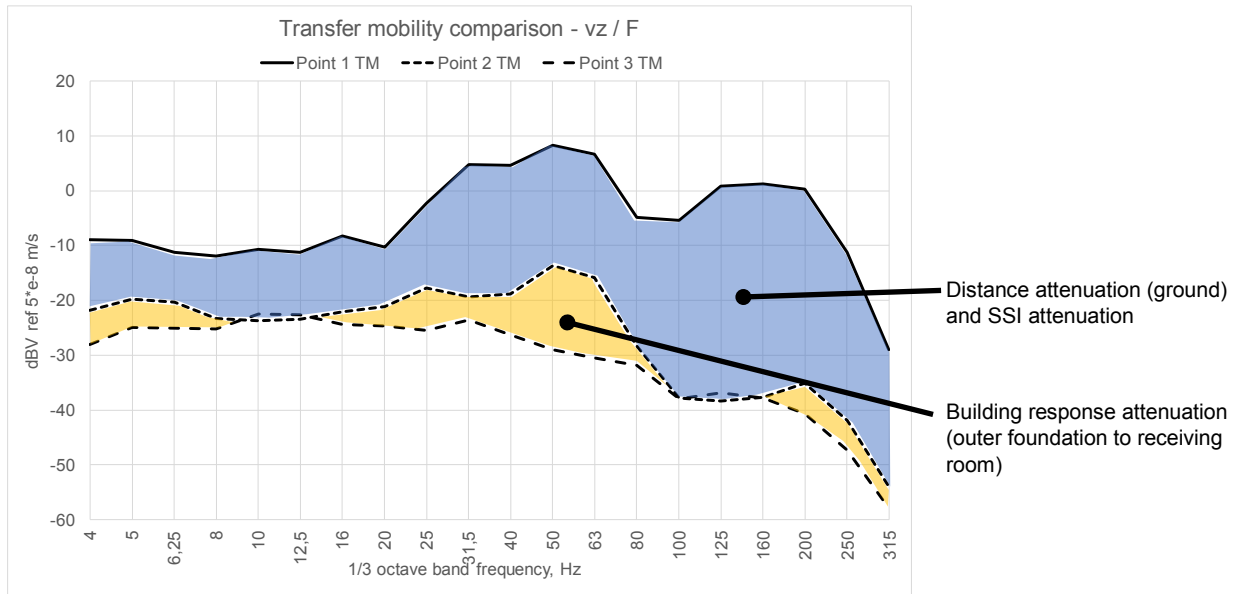


Figure 12: Transfer mobility comparison

Finally, the Point 3 TM curve gives an indication of the transfer mobility between a point located about 15 m underground in the worksite area and a point located in a sensitive room inside the nearest building.

This data is useful for assessing the impact of future works. By applying this transfer mobility to the force of each construction activity, the groundborne vibration impact inside the building can easily be estimated, as well as the groundborne noise impact.

6 BIBLIOGRAPHIC DATA COMPARISON

For comparison, we can estimate the transfer mobility by combining the available bibliographic data collected in the FTA transit noise and vibration assessment guide, as illustrated below.

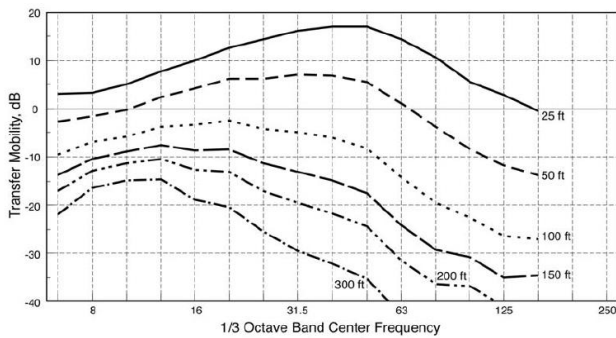


Figure 11-3. Example of Point-Source Transfer Mobility

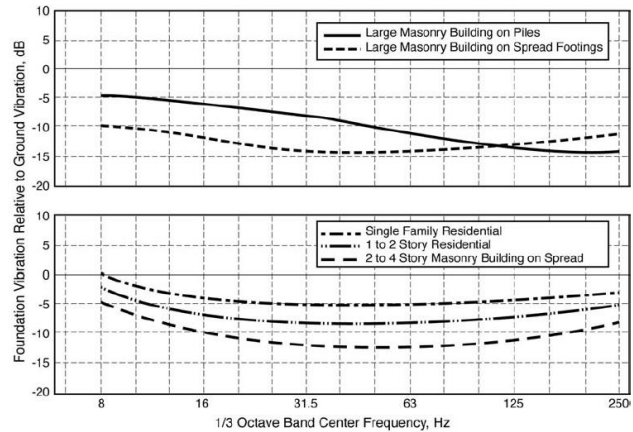


Figure 11-5. Foundation Response for Various Types of Buildings

Figure 13: Transfer mobility literature [2]#

The following graph compares the transfer mobility measured on site to the transfer mobility estimated based on the FTA curves for a large 2 to 4 stories masonry building on spread footings.

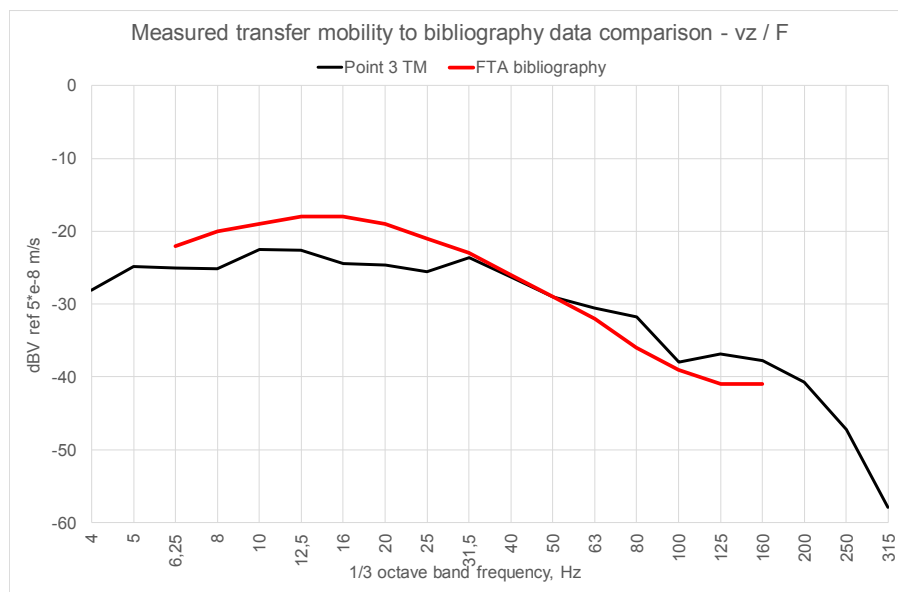


Figure 14: Measured transfer mobility compared to FTA data

As we can see, the two curves are quite similar, even though the FTA derived curve is ideal and given for homogeneous ground conditions.

Given the fact that the reference point is underground and that the test building has a complex morphology, the differences are not unexpected.

Moreover, test results provide a better knowledge of the transfer mobility for the test site and for a larger frequency range, which could be more suited for ground-borne noise analysis.

7 CONCLUSION

In this paper, we have discussed the results of a series of vibration transfer mobility tests on a worksite in Saint-Cloud (France). The focus of these tests was to estimate the transfer mobility over a large zone based on an alternative measurement method, using both an impact hammer and a falling weight.

The intermediate estimation of the local transfer mobility around the impact point can provide an approximation the falling weight force and on the global transfer mobility.

The test results are also compared to the bibliographic references available, and the similarity between the two sets of data confirms the general applicability of this kind of assessment.

8 REFERENCES

- Federal Transit Administration, Transit Noise and Vibration Impact Assessment, (1995). Report DOT, Number DOT-T-95-16, April 1995.
- Nelson, J.T. and Saurenman, H.J. (1988). "A Prediction Procedure for Rail Transportation Ground-Borne Noise and Vibration," Transportation Research Record 1143, August 1988 2. U.S.
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- Verbraken, H., (2012), "Degrande, G. and Lombaert, G. Experimental and numerical determination of transfer functions along railway tracks". Volume 13, Issue 11, pp 802–813.