Estimating maximum Fast time-weighted vibration levels from short equivalent continuous vibration level measurements of structure-borne sound sources on heavyweight plates

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Summary
Characterisation of the structure-borne sound power according to EN 15657 provides input data for the prediction model in EN 12354-5. This allows the prediction of sound transmission based on building machinery running under steady-state conditions. However, most machinery runs in cycles which results in a time-varying power input into the building structure. For this reason, some European countries specify the noise requirements using the maximum Fast time-weighted sound pressure level. The overall aim of this work is to assess whether short (125ms) equivalent continuous vibration measurements in one-third octave bands on the reception plate have the potential to be used to determine a time-varying structure-borne sound power in short time intervals. This could then be used in EN12354-5 to estimate the short (125ms) equivalent continuous sound pressure level in an adjacent room with an empirical correction to estimate the maximum Fast time-weighted sound pressure level. In this paper, idealised time-varying signals were created to compare maximum Fast time-weighted levels with the short (125ms) continuous equivalent levels. Empirical corrections are developed that can be used to estimate Fast time-weighted maximum levels from short equivalent levels.

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1. Introduction

To characterise steady-state structure-borne sound sources, the reception plate method in EN 15657 [1] is used as a laboratory measurement for building machinery. This approach provides input data for EN 12354-5 [2] to predict sound levels in a room due to mechanical excitation from the building machinery. These standards are based on the use of equivalent continuous sound and vibration levels and assume stationary signals. However, there are many types of building machinery that are cyclic and have a time-varying vibrational power output. For this reason, it is common for European regulations on installation noise to set requirements in the receiving room based on the maximum Fast time-weighted sound pressure level. These maximum levels can potentially be predicted with Transient SEA (TSEA) [3,4,5] but this is significantly more complex than the EN 12354-5 prediction model [2].

This paper investigates whether the heavyweight reception plate could be used to quantify the structure-borne sound power of time-varying sources using short (125ms) equivalent continuous vibration levels to capture the time-varying power input. Rather than use real machinery, this paper considers idealised time-varying signals to compare these short equivalent continuous vibration levels with maximum Fast time-weighted vibration levels in one-third octave bands from 20Hz to 6.3kHz. The aim is to assess the potential for an empirical correction that could be used to estimate maximum Fast time-weighted levels from short equivalent continuous levels. If this was feasible, then future work could consider using EN12354-5 [2] with a structure-borne sound power input that corresponded to the maximum power input over a short time period. The empirical correction could then be used to estimate maximum Fast time-weighted sound pressure levels.

2. Signal processing

Wav files of time-varying signals are created to ensure repeatability and reproducibility. The reference measurement is the signal played directly into the measurement system. This is compared to measurements where the signal is sent to an electrodynamic shaker into a heavyweight reception plate and a concrete floor in the building-like situation. As a benchmark, a wav file of 5s of white noise is also considered.

2.1. Idealized time-varying signals

The time-varying signals are generated in Matlab and consist of a temporally varying envelope of white noise involving a rising and falling ramp. Each signal begins with 1s of white noise, followed by a rising ramp and a falling ramp, each of the same duration. Twenty wav files are created using ramp durations of 125ms, 500ms, 1s, 2s and 5s with level increases/decreases over each ramp of 10dB, 20dB, 30dB and 40dB (see example in Figure 1).

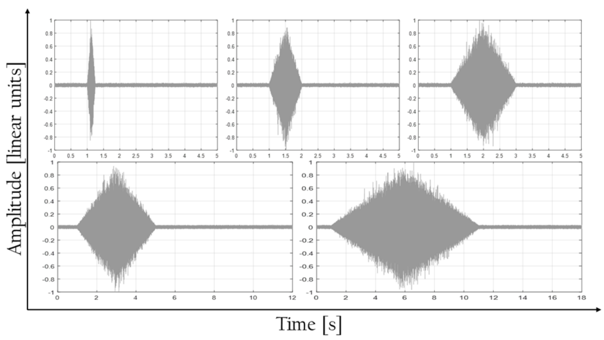

Figure 1. Example of time-varying signals for all five ramps with a 30 dB change in level. 125ms ramp (upper left graph). 500ms ramp (upper middle graph). 1s ramp (upper right graph). 2s ramp (lower left graph). 5s ramp (lower right graph).

2.2. Processing of short L_{eq} and L_{Fmax} levels

Simultaneous measurements of the maximum Fast time-weighted level and the short equivalent continuous level are carried out over one-third octave bands from 20Hz to 6.3kHz.

The Fast time-weighted levels are measured using exponential averaging, Fast time-weighting (125ms) and the maximum hold function which gives L_{Fmax} in one-third octave bands.

The short equivalent levels are measured as linear functions with levels that are time- and frequency-dependent using time steps of 125ms. The highest level in each frequency band from 20Hz to 6.3kHz defines the maximum linear short equivalent continuous levels, given by max $\{L_{eq,125ms}\}$ in one-third octave bands.

The difference between the short equivalent continuous level and the maximum Fast time-weighted level leads to an empirical correction. This correction is initially calculated from the signals that are played directly into the measurement system and subsequently from the experimental work on the horizontal concrete reception plate and the concrete floor in the building-like situation.

2.3. Experimental work

The time-varying signal is played into an electrodynamic shaker that is connected to (a) a horizontal concrete reception plate and (b) a concrete floor in the building-like situation.

2.3.1. Test constructions

The heavyweight reception plate test rig (Figure 2) consists of three decoupled 100mm concrete plates (areas ranging from 5.34m² to 6.85m²) that are perpendicular to each other and supported around the edges by viscoelastic material [6]. The experimental work in this paper uses the horizontal reception plate (area of 5.60m²).

Figure 2. Reception plate test rig at Stuttgart.

Field measurements were carried out on a concrete floor located in a test facility for impact sound measurements in the laboratory at Stuttgart representing a building-like situation as shown in Figure 3. The concrete separating floor is 140mm thick and has an area of 19.41m². The floor test facility comprises two reverberation rooms with suppressed flanking transmission due to independent linings on the walls.

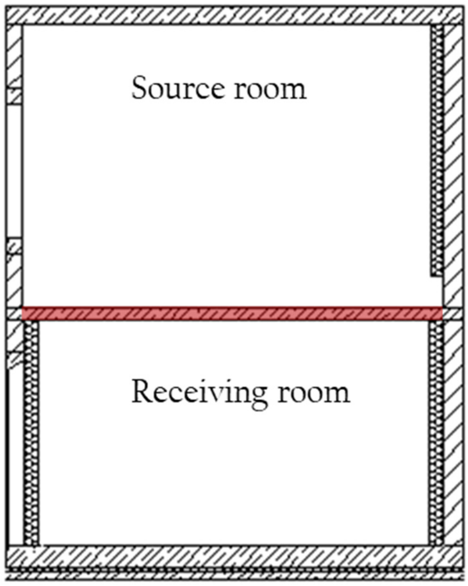

Figure 3. Floor test facility at Stuttgart.

The structural reverberation times of the reception plate and the separating floor are shown in Figure 4. Below 250Hz, the structural reverberation time is higher for the concrete floor in the building-like situation than for the horizontal concrete reception plate, and above 250Hz they are similar.

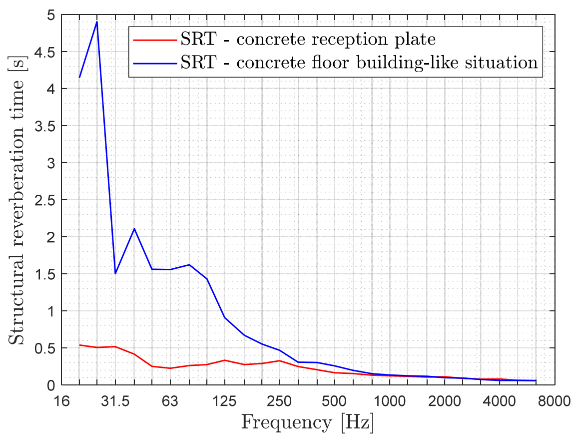

Figure 4. Measured structural reverberation times of the concrete reception plate and the concrete floor in the building-like situation.

The mean free path is 1.83m for the reception plate and 3.46m for the concrete floor in the building-like situation. Converting this distance into the time taken for bending waves to travel the mean free path gives a range from 32ms at 20Hz to 2ms at 6.3kHz for the reception plate, and 13ms at 20Hz to 1ms at 6.3kHz for the floor in the building-like situation. As these times are all smaller than the 125ms time step, the choice of 125ms is reasonable and worthy of assessing.

2.3.2. Procedures

An electrodynamic shaker was installed at three different excitation positions on each plate - see Figures 5 and 6. On the reception plate the spatial-average velocity is measured at nine positions including five positions in the central zone ($\geq$ 0.5m away from edges) and four corners using the weighting factor proposed in [6,7]. On the concrete floor the spatial-average velocity is obtained from seven positions which are randomly distributed close to corners/edges and central zone.

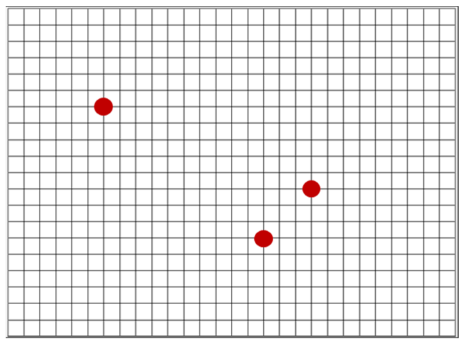

Figure 5. Excitation positions on the horizontal concrete reception plate.

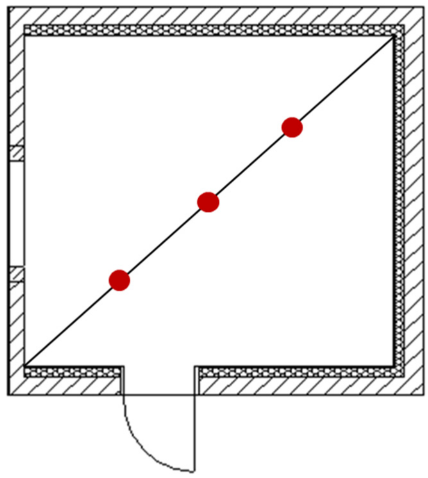

Figure 6. Excitation positions on the concrete floor in the building-like situation.

3. Results

The results consider the following difference: $\max\{L_{eq,125ms}\}$ - L_{Fmax}.

Figure 7 and Table I shows the results for white noise as a benchmark. With increasing frequency, the difference tends towards 0dB but in the 20Hz one-third octave band filter the difference is ≈ -3dB. Figures 8 to 12 plot the frequency-dependent differences in one-third octave bands, and Tables II to VI give minimum, maximum and frequency average values. Note these are significantly different to the white noise (Figure 7) which indicates the need for a correction term.

The 125ms ramp is expected to be the most demanding situation to identify an empirical correction because it is the same length as the averaging time. However, once the ramp duration is ≥ 500ms the difference values are similar to within 1dB. For the 125ms ramps, the 10dB ramp level gives a difference that is ≈ 1.5dB higher than the curves for the ramp levels of 20/30/40dB over the whole frequency range. In general, the curves for the ramp levels of 20/30/40dB are similar. This feature occurs with the signal played directly into the measurement system, into the shaker on the reception plate and into the shaker on the floor in the building-like situation. As the ramp duration increases the 10dB ramp the level becomes similar to the curves for the 20/30/40dB ramp levels below 125Hz, but above 125Hz it still differs.

Regardless of whether the signal is played directly into the measurement system, into the shaker on the reception plate or into the shaker on the floor in the building-like situation, the curves do not show strong variation with frequency above 125Hz; hence Tables II to VI show the minimum and maximum values as well as the frequency-average value.

For the signal played directly into the measurement system, the average of all the differences in Tables II to VI for the 10dB ramp levels is ≈ 4.9dB. Averaging the differences for the 20/30/40dB ramps gives -7.6dB, -6.1dB, -6.2dB, -6.1dB and -6.2dB for the 125ms, 500ms, 1s, 2s and 5s ramp durations respectively. Considering that the final application is to estimate the maximum Fast time-weighted level in the field situation, and that the prediction in building acoustics to ±3dB is often sufficient, it is reasonable to consider a single average difference of -6.2dB for the 20/30/40dB ramps.

In Tables II to VI the experimental differences measured on the concrete reception plate give similar results to the signal that is played directly into the measurement system. The 10dB ramp levels have the same average difference of ≈ 4.9dB. For the ramp levels of 20/30/40dB the differences are -7.2dB, -6.3dB, -5.9dB, -5.9dB and -6.2dB for the 125ms, 500ms, 1s, 2s and 5s ramp durations. These only differ by 0.5dB from the values when the signal is played directly into the measurement system. As before, a single average difference is calculated which is -6.2dB.

Similarly, for the measurements on the concrete floor in the building-like situation, the average value for the 10dB ramp levels is ≈ 5.1dB; this is within ≈ 1dB of the value for the signal directly played into the measurement system. For ramp levels with 20/30/40dB the differences are -6.9dB, -6.2dB, -6.0dB, -5.9dB and -6.6dB for ramp durations of 125ms, 500ms, 1s, 2s and 5s. This gives a single average difference of -6.2dB.

In summary, the results indicate that for ramp levels of (a) 10dB for all ramp durations it is reasonable to assume that $\max\{L_{eq,125ms}\} - L_{Fmax} \approx 5$dB, (b) 20/30/40dB with a ramp duration of 125ms it is reasonable to assume that $\max\{L_{eq,125ms}\} - L_{Fmax} \approx 7.5$dB, and (c) 20/30/40dB with ramp durations ≥ 500ms it is reasonable to assume that $\max\{L_{eq,125ms}\} - L_{Fmax} \approx 6$dB.

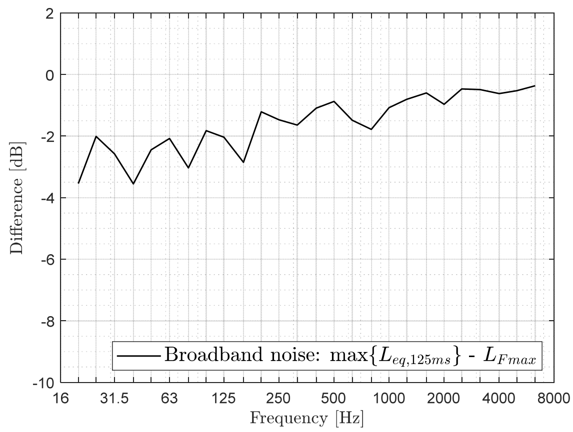

Figure 7. Wav file white noise: Played directly into measurement system.

Table I. White noise levels.

Wav files directly played into measurement system		
MIN max $\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
-0.3	-3.6	-1.4

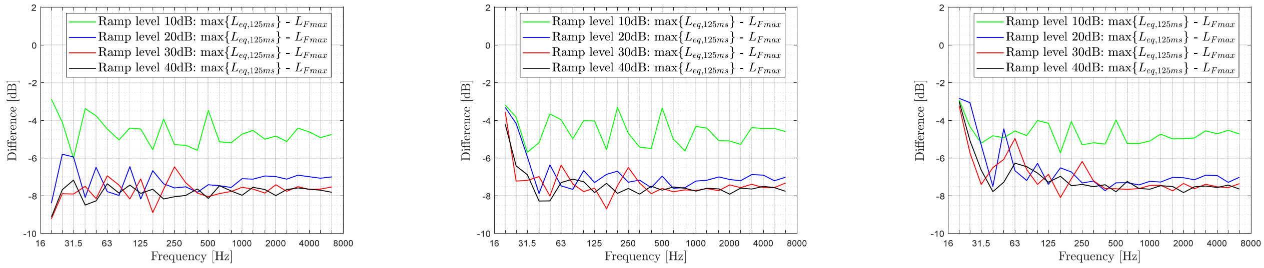

Figure 8. Wav files 125ms ramp with 10/20/30/40dB levels: (Left) played directly into measurement system. (Middle) played into shaker on reception plate. (Right) played directly into shaker on floor in building-like situation.

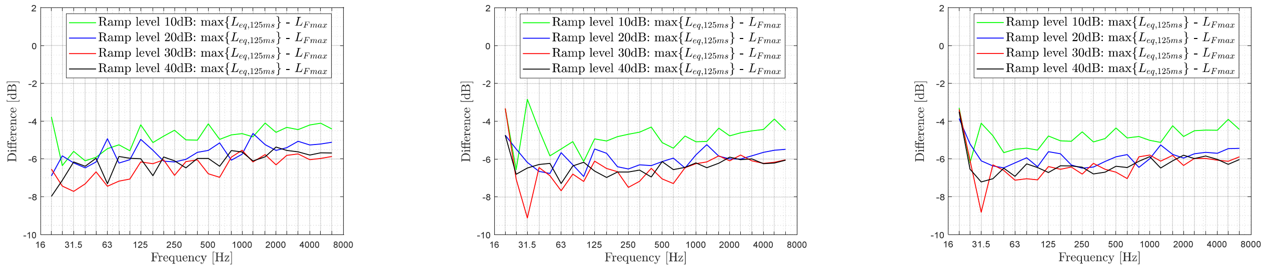

Figure 9. Wav files 500ms ramp with 10/20/30/40dB levels: (Left) played directly into measurement system. (Middle) played into shaker on reception plate. (Right) played directly into shaker on floor in building-like situation.

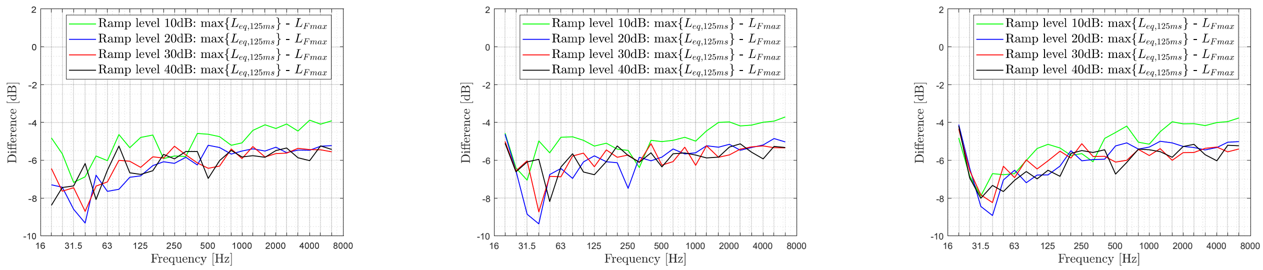

Figure 10. Wav files 1s ramp with 10/20/30/40dB levels: (Left) played directly into measurement system. (Middle) played into shaker on reception plate. (Right) played directly into shaker on floor in building-like situation.

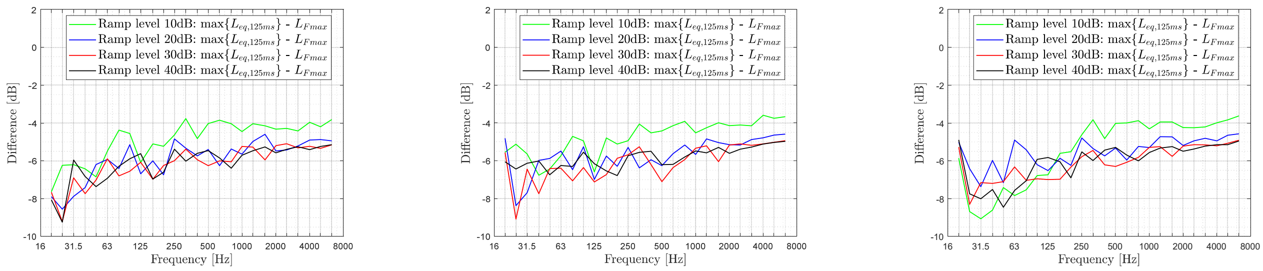

Figure 11. Wav files 2s ramp with 10/20/30/40dB levels: (Left) played directly into measurement system. (Middle) played into shaker on reception plate. (Right) played directly into shaker on floor in building-like situation.

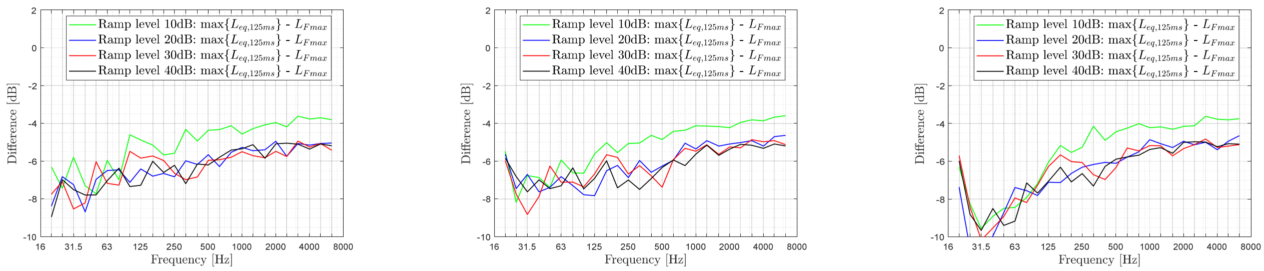

Figure 12. Wav files 5s ramp with 10/20/30/40dB levels: (Left) played directly into measurement system. (Middle) played into shaker on reception plate. (Right) played directly into shaker on floor in building-like situation.

Table II. 125ms ramp with 10/20/30/40dB levels.

Ramp level	Wav files directly played into measurement system			Wav files played into shaker on horizontal reception plate			Wav files played into shaker on concrete floor in building-like situation		
	MIN max $\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
10dB	-2.9	-6.0	-4.6	-3.2	-5.7	-4.6	-2.9	-5.7	-4.7
20dB	-5.8	-8.4	-7.2	-3.3	-7.9	-6.9	-2.8	-7.7	-6.6
30dB	-6.5	-9.2	-7.7	-3.6	-8.7	-7.3	-3.2	-8.1	-7.0
40dB	-7.2	-9.1	-7.8	-4.2	-8.3	-7.4	-3.0	-7.8	-7.1

Table III. 500ms ramp with 10/20/30/40dB levels.

Ramp level	Wav files directly played into measurement system			Wav files played into shaker on horizontal reception plate			Wav files played into shaker on concrete floor in building-like situation		
	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
10dB	-3.8	-6.4	-4.8	-2.8	-6.6	-4.8	-3.3	-6.2	-4.8
20dB	-4.6	-6.9	-5.7	-4.7	-6.9	-6.0	-3.9	-6.5	-5.9
30dB	-5.5	-7.7	-6.4	-3.3	-9.1	-6.6	-3.4	-8.8	-6.4
40dB	-5.4	-8.0	-6.1	-4.7	-7.3	-6.4	-3.5	-7.2	-6.3

Table IV. 1s ramp with 10/20/30/40dB levels.

Ramp level	Wav files directly played into measurement system			Wav files played into shaker on horizontal reception plate			Wav files played into shaker on concrete floor in building-like situation		
	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
10dB	-3.9	-7.2	-5.0	-3.7	-7.0	-4.9	-3.8	-7.9	-5.2
20dB	-5.2	-9.3	-6.3	-4.6	-9.4	-6.0	-4.1	-8.9	-5.9
30dB	-5.3	-8.7	-6.2	-5.0	-8.7	-5.9	-4.3	-8.2	-5.9
40dB	-5.2	-8.4	-6.2	-5.1	-8.2	-5.9	-4.2	-8.0	-6.1

Table V. 2s ramp with 10/20/30/40dB levels.

Ramp level	Wav files directly played into measurement system			Wav files played into shaker on horizontal reception plate			Wav files played into shaker on concrete floor in building-like situation		
	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
10dB	-3.8	-7.6	-4.9	-3.6	-6.8	-4.8	-3.6	-9.1	-5.4
20dB	-4.6	-8.6	-5.9	-4.6	-8.4	-5.7	-4.6	-7.4	-5.5
30dB	-5.1	-9.2	-6.2	-4.9	-9.1	-6.1	-4.9	-8.3	-6.0
40dB	-5.1	-9.2	-6.1	-5.0	-6.9	-5.8	-4.9	-8.5	-6.1

Table VI. 5s ramp with 10/20/30/40dB levels.

Ramp level	Wav files directly played into measurement system			Wav files played into shaker on horizontal reception plate			Wav files played into shaker on concrete floor in building-like situation		
	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MIN max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	MAX max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)	AVG max$\{L_{eq,125ms}\}$ - L_{Fmax} (estimated)
10dB	-3.6	-7.7	-5.1	-3.6	-8.2	-5.2	-3.2	-9.7	-5.6
20dB	-4.9	-8.7	-6.2	-4.6	-7.8	-6.1	-4.8	-9.1	-6.6
30dB	-4.9	-8.5	-6.2	-4.9	-8.8	-6.2	-4.9	-8.3	-6.5
40dB	-5.1	-9.0	-6.3	-5.1	-7.6	-6.3	-4.9	-7.6	-6.6

4. Conclusions

This paper considered the difference between maximum Fast time-weighted vibration levels and the maximum short (125ms) equivalent continuous level in one-third octave bands. A comparison of these differences was carried out for (a) a time-varying signal played directly into the measurement system, (b) a time-varying signal played into a shaker on a concrete reception plate and (c) a time-varying signal played into a shaker on a concrete floor in the building-like situation). The time-varying signal comprised different rising and falling ramp durations of 125ms to 5s with increasing and decreasing ramp levels from 10dB to 40dB.

In summary, the results indicate that for ramp levels of (a) 10dB for all ramp durations it is reasonable to assume that $\max\{L_{\mathrm{eq,125ms}}\} - L_{\mathrm{Fmax}} \approx 5$dB, (b) 20/30/40dB with a ramp duration of 125ms it is reasonable to assume that $\max\{L_{\mathrm{eq,125ms}}\} - L_{\mathrm{Fmax}} \approx 7.5$dB, and (c) 20/30/40dB with ramp durations ≥ 500ms it is reasonable to assume that $\max\{L_{\mathrm{eq,125ms}}\} - L_{\mathrm{Fmax}} \approx 6$dB.

The next stage of the research is to estimate the maximum Fast time-weighted sound pressure level in the building-like situation using EN12354-5 with a structure-borne sound power input that corresponds to the maximum power input over a short time period by making use of the empirical correction.

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