Characterisation of time-varying structure-borne sound sources using a reception plate to predict maximum Fast time-weighted levels in heavyweight buildings

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ABSTRACT

Structure-borne excitation from many mechanical appliances leads to structural vibration in buildings which can be transmitted to nearby rooms. The reception plate method provides a characterisation procedure to obtain the power input for SEA prediction models. Earlier work developed empirical corrections based on the relationship between $L_{\mathrm{eq,125ms}}$ *and* L_{Fmax} *to predict sound transmission from time-varying sources in buildings. For this purpose, the reception plate method is used to capture the maximum power input over a short time period. Using different ramped noise signals to represent idealised versions of time-varying signals from machinery allowed empirical corrections to be identified such that* $L_{\mathrm{eq,125ms}}$ *measurements can be used with the reception plate. When using SEA or EN 12354, it is shown that* L_{Fmax} *in a room can be predicted for a time-varying structure-borne sound source with one-third octave band errors within 3 dB. Similar or better results occurred for the predicted* L_{AFmax} *that was calculated from one-third octave band* L_{Fmax} *values. Reception plate measurements were carried out on a sanitary installation using the toilet flush to compare the empirical corrections with those from ramped noise signals. Close agreement indicated that the empirical corrections are also applicable to a real, and more complex, time-varying source.*

1. INTRODUCTION

Structure-borne sound, which is injected into the building structure by mechanical appliances such as washing machines, boilers, sanitary installation systems, heat pumps, etc., can cause noise nuisance for occupants when transmitted to adjacent rooms. To characterise the steady-state structure-borne sound source, the reception plate method described in EN 15657 [1] can be used to obtain the steady-state power input data. This power can then be used in prediction models based on Statistical Energy Analysis (SEA) to estimate equivalent continuous levels, L_{eq}, according to EN 12354-5 [2]. Since domestic appliances have different operating cycles, they will transmit time-varying structure-borne sound power into the building structure. For this reason, it is common practice in European building

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regulations on installation noise (e.g. SIA 181 [3] and VDI 4100 [4]) to set requirements using a maximum Fast time-weighted sound pressure level, L_{Fmax} in frequency bands and/or L_{AFmax}, in the receiving room.

In heavyweight buildings, the prediction of L_{Fmax} and L_{AFmax} from heavy impacts can be estimated using Transient SEA (TSEA) [5,6]. Although TSEA could be used for mechanical building appliances or machinery with time-varying operating phases, the model is likely to be too complex to be incorporated into European or International Standards. Hence, a simplified approach that could encourage industry would be to modify an SEA-based model such as that in EN 12354-5. In previous work [7,8], an approach based on an empirical weighting factor was identified that might encourage uptake by industry due to its relative simplicity. An SEA-based prediction model relating to EN 12354-5 was therefore developed to predict L_{Fmax}. As input data from time-varying structure-borne sound sources for SEA predictions, the maximum injected power over a 125 ms period in the form of a maximum short equivalent continuous velocity level, $\max\{L_{\mathrm{eq,125ms}}\}$ (based on the Fast time constant of 125 ms), is measured with the reception plate method described in EN 15657.

This paper reviews the approach to the prediction of L_{AFmax} in rooms from energetically summed L_{Fmax} levels in one-third octave bands that has been obtained from predicted $\max\{L_{\mathrm{eq,125ms}}\}$ levels in combination with a single-number empirical correction. To provide evidence of the applicability of the empirical correction to real structure-borne sound sources, a case study is carried out to investigate the empirical link between L_{Fmax} and $\max\{L_{\mathrm{eq,125ms}}\}$ with a time-varying structure-borne sound signal from a sanitary installation on the reception plate.

2. PREDICTION OF L_{Fmax} LEVELS FROM SHORT L_{eq} LEVELS WITH SEA

For steady-state sound transmission in buildings, an SEA model of a coupled room-plate system can be used to model energy exchange between a coupled homogenous plate (subsystem 1) and a receiving room (subsystem 2). Considering the power input into the plate (subsystem 1), internal losses and coupling losses between the two subsystems [9,10], the power balance equations for a coupled room-plate system can be written as

$$\begin{aligned} W_{\mathrm{in},1} &= \omega(\eta_{11}E_1 + \eta_{12}E_1 - \eta_{21}E_2) \\ 0 &= \omega(\eta_{22}E_2 + \eta_{21}E_2 - \eta_{12}E_1) \end{aligned} \tag{1}$$

where $W_{\mathrm{in},1}$ is the power input applied to the plate (subsystem 1), η_{11} is the internal loss factor of the plate (subsystem 1), η_{22} is the internal loss factor of the receiving room due to sound absorption (subsystem 2), η_{12} and η_{21} are the coupling losses from the plate (subsystem 1) to the receiving room (subsystem 2) and vice versa.

Eq. (1) is solved to give the plate and room energies. The temporal and spatial average mean-square sound pressure, $\langle p^2 \rangle_{t,s}$, is calculated from the room energy using

$$E_2 = \frac{V_2 \langle p^2 \rangle_{t,s}}{\rho_0 c_0^2} \tag{2}$$

where V_2 is the volume of the receiving room, ρ_0 and c_0 are the density and the speed of sound in air respectively. Experimental work was used to determine the vibrational power input [11], the radiation efficiency, the loss factors of the plate and the receiving room, and the coupling loss factors between the plate and the room [8].

SEA or simplified SEA-based models (e.g. EN 12354-5) for building machinery are mainly used for relatively long steady-state time periods during an operating cycle. The majority of building machinery/equipment runs with cyclic signals ramping up and down; hence, some European building regulations on installation noise [3,4] set their requirements using L_{Fmax}. Therefore, an empirical link between L_{Fmax} and $\max\{L_{\mathrm{eq,125ms}}\}$ was determined in previous work [7,8]. This used an idealised source of ramped white noise signals with ramp durations of 125 ms to 5 s and ramp levels from 10 dB to 40 dB. The resulting empirical corrections allowed L_{Fmax} levels to be predicted from $\max\{L_{\mathrm{eq,125ms}}\}$. However, these corrections showed some dependency on ramp duration and ramp level. The empirical correction was 5 dB for all ramp durations with a ramp level of 10 dB, 7.5 dB for a ramp duration of 125 ms with ramp levels of 20/30/40 dB and 6 dB for ramp durations ≥500 ms with ramp levels of 20/30/40 dB. To simplify the approach, a single-number empirical correction of 6 dB was proposed for use with SEA-based models such as EN 12354-5.

3. EXPERIMENTAL SET-UP

Laboratory experiments with time-varying structure-borne sound sources were carried out on a reception plate test rig and a heavyweight floor test facility for direct sound transmission.

3.1. Reception plate

The reception plate test rig consists of three 100 mm concrete plates that are structurally isolated and arranged in the three coordinate planes. They are supported around the edges by viscoelastic material to provide additional damping. The measurements in this paper used the horizontal reception plate (2.80 m × 2.00 m) and the larger vertical plate (3.10 m × 2.21 m).

3.2. Building-like situation with suppressed flanking transmission

The floor test facility compromises a source and receiving room which is separated by a reinforced concrete floor representing the building-like situation for field measurements. The rooms have wall linings to suppress flanking sound transmission so that the dominant sound transmission takes place via the concrete floor into the receiving room. The concrete floor is 140 mm thick with an area of 19.4 m² (4.60 m × 4.22 m) and the receiving room has a volume of 51.1 m³ (4.60 m × 4.22 m × 2.63 m).

4. RESULTS FROM RAMPED NOISE SIGNALS

For SEA predictions and field measurements of L_{AFmax} levels for direct sound transmission in the receiving room, the ramped noise signals were directly played into a shaker on the concrete floor in the heavyweight building-like situation. The single-number empirical correction was used to predict L_{Fmax} from the SEA model and L_{AFmax} was predicted from the A-weighted and energetically summed L_{Fmax} levels in one-third octave bands. Figure 1 allows comparison of measured and predicted L_{AFmax} levels. The results indicate that the largest offset errors (up to 2.5 dB) occur for all ramp durations with the 10 dB ramp level. However, for all other ramp levels higher than 10 dB, the differences are from -0.4 dB to 0.7 dB. These errors can be considered as very low for most applications in building acoustics.

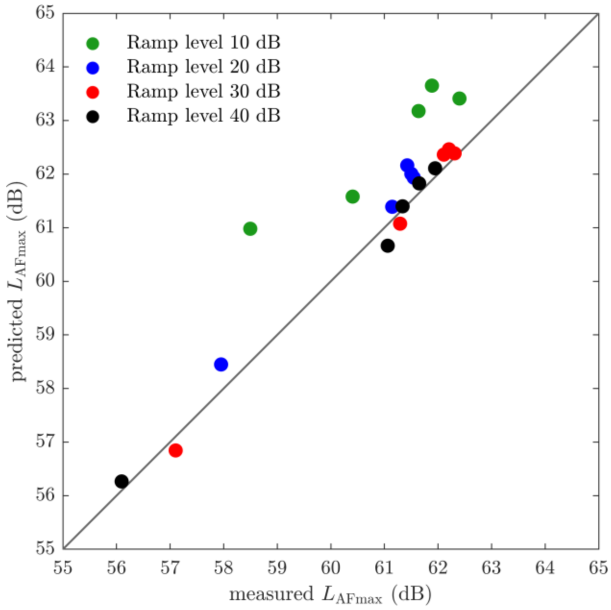

Figure 1: Ramped noise signals: Comparison of predicted and measured L_{AFmax} levels in the receiving room for direct sound transmission in the heavyweight building-like situation.

5. CASE STUDY: SANITARY INSTALLATION SYSTEM

The previous section confirms that it is possible to predict sound and vibration transmission from a ramped broadband noise signal that mechanically excites a structure and predict L_{Fmax} and L_{AFmax} in a receiving room. In this section, a real structure-borne sound source is considered in terms of characterisation that requires both the horizontal and vertical reception plates. This provides an opportunity to confirm the validity of the single-number empirical correction with a much more complex time-varying signal.

Figure 2(a) and (b) show the sanitary installation system (Geberit GIS) on the horizontal and vertical reception plates. Figure 2(c) shows that the highest velocity levels (using Fast time weighting without any frequency weighting) on the reception plate occur during the flushing process rather than the refilling process. Hence, the focus in this section is on the three ramps (A, B and C) that occur during the flushing process.

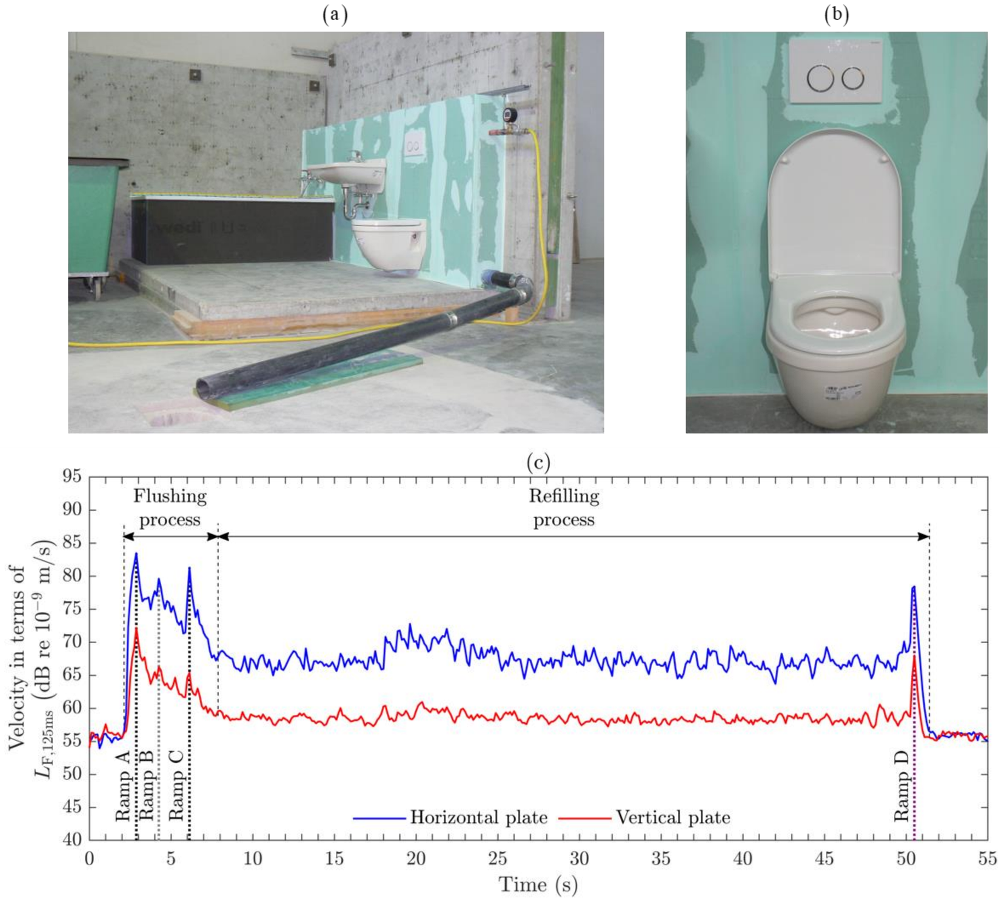

Figure 2: Case study: (a) measurement set-up for the sanitary installation system (Geberit GIS), (b) the toilet and (c) the summed velocity levels in one-third octave bands over time with defined ramps A, B, C and D using $L_{F,125ms}$ in the free run of a toilet flush cycle on the horizontal and vertical reception plates.

A more detailed graph of the flushing process is shown in Figures 3 and 4 for the horizontal and vertical reception plates respectively. Figures 3 and 4 (a) show that the peaks in ramps A, B and C occur at 2.875, 4.25 and 6.125 s respectively. However, the peaks in the one-third octave band levels do not necessarily occur at these times; hence, Figures 3 and 4 (b) – (k) show the highest peak in ramps A and C in the 50, 250, 500, 1k and 2k Hz one-third octave bands. Note that it is the increasing ramp (rather than the decreasing ramp) that is more important in determining L_{Fmax}.

The horizontal reception plate had higher $L_{F,125ms}$ values than the vertical reception plate, and therefore it also had the highest increasing ramp levels. Considering both reception plates for ramp A, the increasing ramp level varied from 8 dB to 29 dB and the general trend is that this ramp level decreased with increasing frequency from 50 Hz to 2k Hz. The ramp durations varied from 375 ms to 750 ms. Previous work with the ramped broadband noise showed that the empirical correction was ≈6 dB for increasing ramp levels of 20 dB to 40 dB (for ramp durations between 500 ms and 5 s), but for a 10 dB ramp level, it was slightly lower (≈5 dB). For ramp A, the majority of ramp levels are >10 dB in the frequency range which indicates that the use of a single-number empirical correction might be reasonable, and this will be assessed shortly. This shows that the empirical corrections determined in the previous work [7] are relevant to this real structure-borne sound source.

One of the complex issues with a real time-varying source is that whilst the initial ramp will have a large increase in ramp level above background, subsequent ramps (e.g. ramps B and C) will not have large increases – see Figures 3 and 4 (g) to (k). For this reason, the small increase with ramp B is not considered in detail on Figures 3 and 4. In order to predict L_{Fmax}, it is possible to use the reception plate to measure $\max\{L_{F,125ms}\}$ to quantify the structure-borne sound power input over a time period that extends beyond the peak in ramp A (e.g. the entire flushing time period). If needed, a gate-off trigger can be used on the analyser to just extract $\max\{L_{F,125ms}\}$ from ramp A. When a subsequent ramp (i.e. ramp C) has increasing ramp levels <10 dB, it is unlikely to be possible to accurately predict the L_{Fmax} that is only due to that ramp. However, in assessing noise nuisance it will often be more useful to predict both L_{Fmax} and L_{eq} for a time-varying source that continues over a relatively long period of time. For example, during the flushing process, there is a ≈3 s time period between ramps A and C (or a ≈5 s time period after ramp A) over which the source could be treated as a steady-state signal using the approach already described in EN 15657 and EN 12354-5.

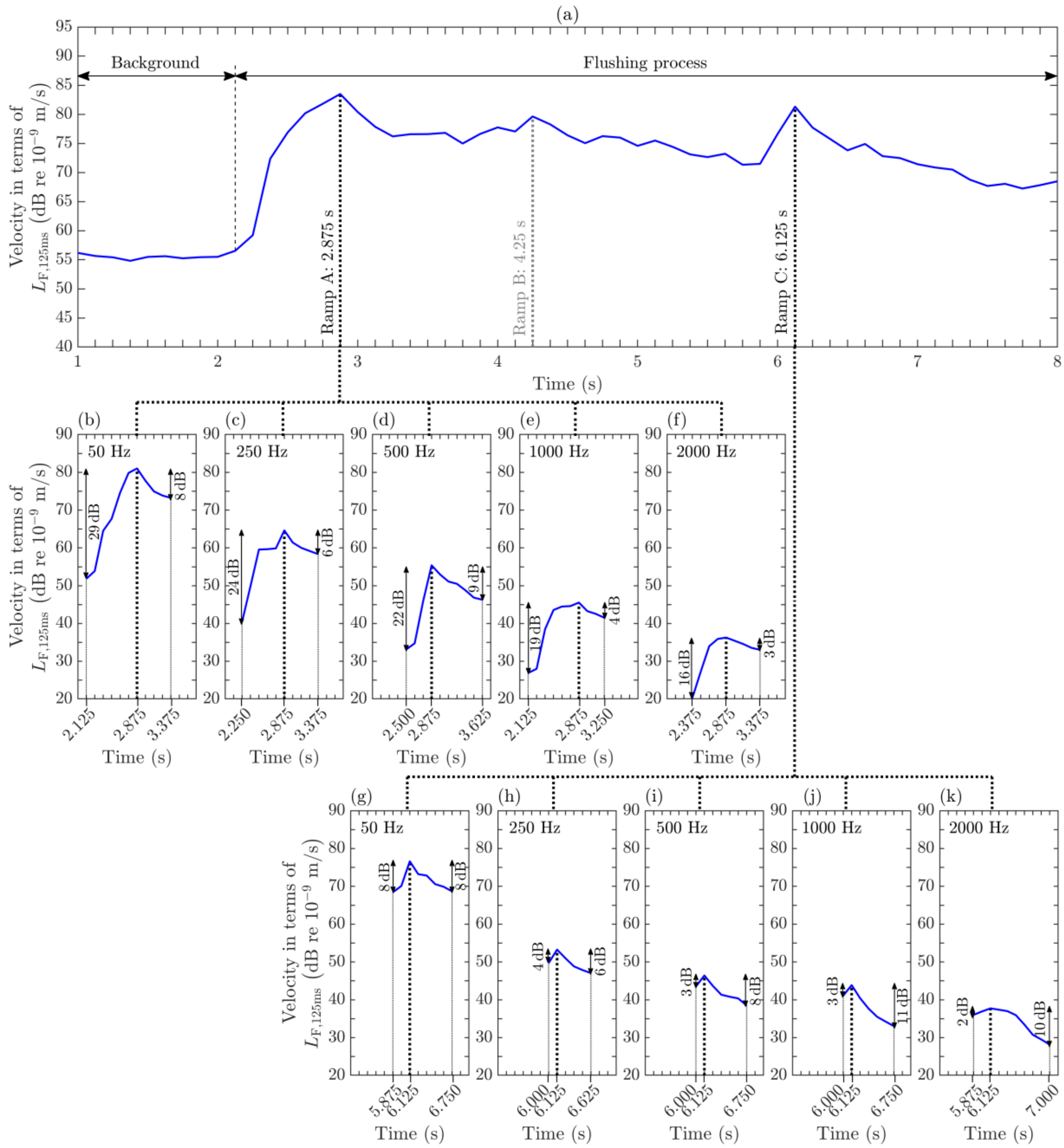

Figure 3: Case study using the horizontal reception plate: (a) the summed velocity level in one-third octave bands over time using $L_{F,125ms}$ in the free run of the first 8 s of a toilet flush cycle, (b) to (f) show one-third octave band velocities for ramp A, (g) to (k) show one-third octave band velocities for ramp C.

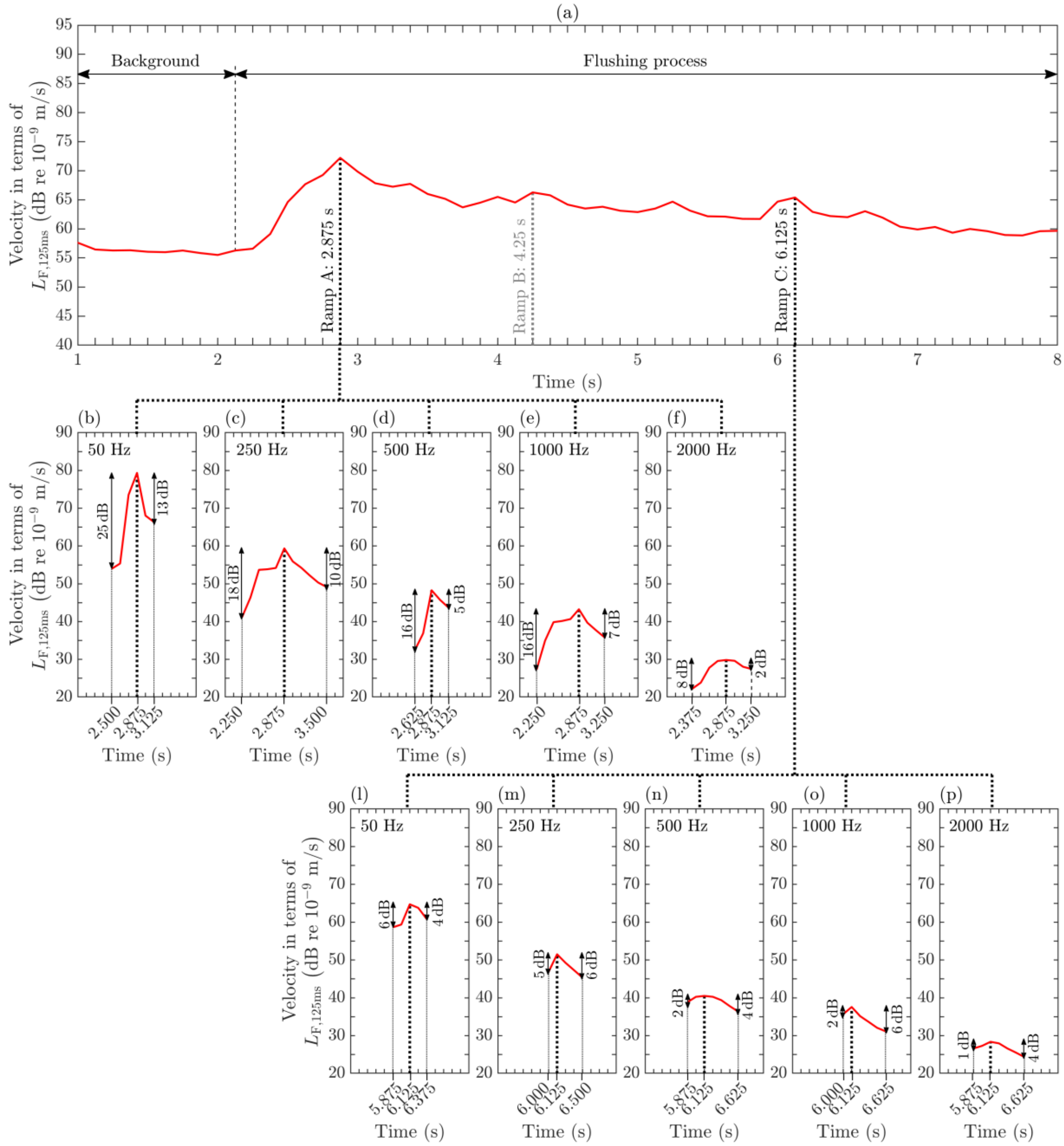

Figure 4: Case study using the vertical reception plate: (a) the summed velocity level in one-third octave bands over time using $L_{F,125ms}$ in the free run of the first 8 s of a toilet flush cycle, (b) to (f) show one-third octave band velocities for ramp A, (g) to (k) show one-third octave band velocities for ramp C.

From Figures 2(c), 3 and 4, it can be seen that there are well-separated, pronounced peaks in the plate velocity for which the highest peak of the summed velocity on the horizontal and vertical reception plates occurred with ramp A. For ramp A, Figures 3 and 4 (b) to (f) indicate that the ramp durations and ramp levels differ between the several frequency bands; hence, there can be identified ramp durations from 125 ms to 1 s and ramp levels from 10 dB to 30 dB. These variations in ramp durations and ramp levels are due to the complexity of a pre-wall installation system with vibrational power into two reception plates.

To check the repeatability of the velocity from ramp A on the horizontal reception plate, six toilet flush cycles were measured in terms of one-third octave band L_{Fmax} velocity levels as shown in Figure 5. The variation in each frequency band ranges from 1 dB to 6 dB over the frequency range from 50 Hz to 3.15k Hz which indicates reasonable repeatability for ramp A from the toilet flush cycle as a complex structure-borne sound source.

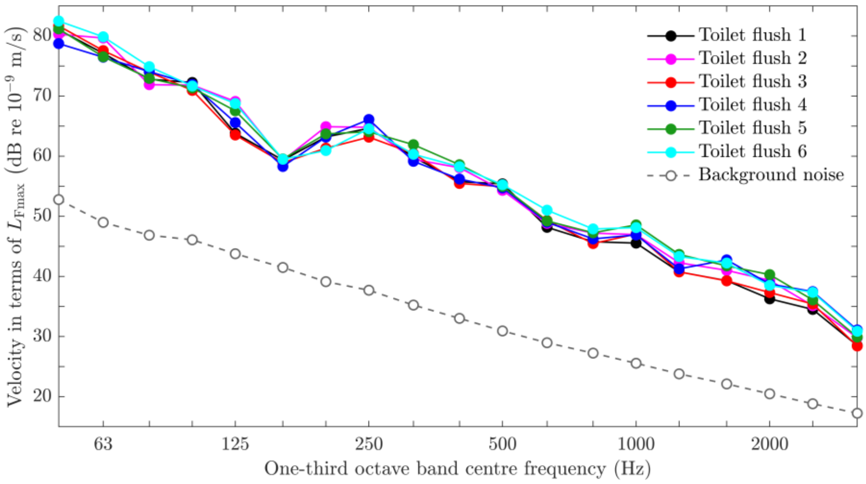

Figure 5: Case study: Repeatability using L_{Fmax} measurements of ramp A from six toilet flush cycles on the horizontal reception plate.

To assess whether the single-number empirical correction from ramped white noise signals can be replicated with ramp A of the toilet flush cycle, the difference $L_{Fmax} - \max\{L_{eq,125ms}\} - 6\,dB$ is calculated. Note that the ramped noise signals played into a shaker on the horizontal reception plate were measured using an area weighting approach to sample the plate velocity levels [11], whereas the toilet flush cycle was determined with an empirical weighting approach when sampling the velocity [12] on the two individual reception plates. This is because the area-weighted approach had not been finalised when carrying out the latter measurements. However, the focus in this paper is on the empirical link between $\max\{L_{eq,125ms}\}$ and L_{Fmax}, and as both sampling strategies differed by only 0.2 dB, the choice of sampling strategy will have negligible effect.

Figure 6 allows comparison of the difference between the ramp- and level-dependent empirical correction and single-number empirical correction for the toilet flush and the ramped noise signals. Note that when the single-number empirical correction of 6 dB is subtracted from the ramp- and level-dependent empirical correction, the average difference between both empirical corrections would ideally be 0 dB. However, a comparison between ramped noise signals having ramp durations of 500 ms and 1 s with ramp levels of 20 dB and 30 dB and ramp A for the toilet flush estimated on the horizontal reception plate indicates that they differ by ≈0.2 dB on average (see Figure 6(a)). When ramp A for the toilet flush is considered on the vertical plate, then the comparison with ramped noise signals with ramp durations of 500 ms and 1 s and ramp levels of 20 dB and 30 dB leads to an average difference of ≈0.3 dB (see Figure 6(b)). Using the 10 dB ramp level from 500 ms and 1 s ramped noise signals, the comparison with ramp A for the toilet flush results in an offset in the average difference of ≈1.2 dB for both reception plates. These results indicate that the ramp durations and ramp levels for ramp A of a toilet flush cycle are more affected by the increasing ramp with ramp levels of >10 dB than on the decreasing ramp with ramp levels of ≤10 dB (refer back to Figure 3 and 4 (b) to (f)).

This case study indicates that a single-number empirical correction of 6 dB would provide a simplified and robust single value to predict L_{Fmax} levels from $\max\{L_{eq,125ms}\}$ levels in heavyweight buildings. Hence, this single-number empirical correction is suitable for consideration with EN 12354-5.

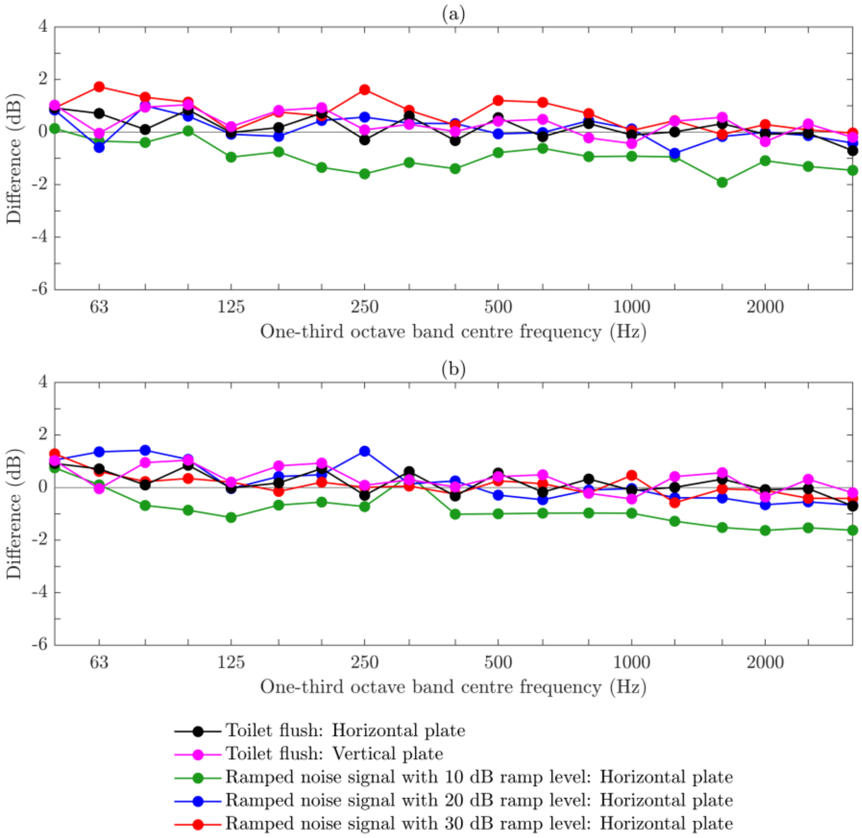

Figure 6: Case study: Comparison of the difference of ramp- and level-dependent empirical corrections minus the single-number empirical correction, $L_{\mathrm{Fmax}} - \max\{L_{\mathrm{eq,125ms}}\} - 6$ dB, for ramp A from a toilet flush cycle and for ramped noise signals from the 500 ms and 1 s ramps with ramp levels of 10/20/30 dB for the (a) horizontal reception plate and (b) vertical reception plate.

6. CONCLUSIONS

An approach to predict maximum Fast time-weighted sound pressure levels from vibrationally active machinery in heavyweight buildings has been developed that can be used with the reception plate method according to EN 15657 and the SEA-based model in EN 12354-5. For this approach, a single-number empirical correction has been established to predict maximum Fast time-weighted sound pressure levels based on ramped broadband noise representing an idealised version of time-varying structure-borne sound power from machinery. This approach is shown to give acceptable accuracy for one-third octave band and A-weighted maximum Fast time-weighted sound pressure levels. To confirm that this is reasonable for real building machinery, a case study of a sanitary installation system with toilet flush has been used to replicate the single-number empirical correction which confirms its validity and practical use. It would be beneficial to investigate more time-varying structure-borne sound sources commonly found in buildings.

7. REFERENCES

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