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Comparison of predicted and measured structure-borne sound of an industrial washing machine on a heavy concrete floor

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ABSTRACT

The Reception Plate Method (RPM) as proposed by CEN/TC126/WG7 in EN 15657-1 estimates the structure-borne sound power injected from a (high mobility) vibrating source into a (low mobility) concrete reception plate. This power level can be used as an input to predict structure-borne sound pressure levels in buildings according to the calculation model in EN 12354-5. To validate both the RPM and the prediction model, measurements are done using two sources: a standard ISO tapping machine and an industrial washing machine placed on three different bases. Both sources are successively placed on the RP and on a concrete floor of a standard impact sound test cell. The sound pressure level in the cell underneath is measured and compared with calculated values. Difficulties in both the test method and the prediction model are investigated.

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1. INTRODUCTION

The recently standardised Reception Plate Method (RPM) in EN 15657-1:2009 [1] estimates the structure-borne sound power injected from a (high mobility) vibrating source into a (low mobility) building structure. Prediction models in EN 12354-5:2009 [2] and EN 12354-1:2000 [3], further allow to calculate the propagation of this injected power towards connected building elements and hence allow to estimate sound pressure levels due to service equipment in buildings. This paper aims to validate both the RPM and the prediction models for the calculation of service equipment noise in a simple building structure.

2. MEASUREMENT SETUP

Measurements have been made using the following structure-borne sound source configurations:

- an ISO tapping machine, put on a 3 mm vinyl.
- an industrial washing machine (160 kg) mounted in three different ways: a) using a heavy-weight (200 kg) concrete base supported by steel feet (case HS); b) using the same concrete base supported by rubber feet (case HR); c) mounted on a MDF plate supported by jacks (case J) (see Figure 1). Also here, all three supports were put on a 3 mm vinyl. The different mountings were chosen to vary the source mobility of the washing machine. An eccentric weight of 1.5 kg was attached to the inside of the drum. Four rotating speeds from 720 rpm up to 1080 rpm have been measured, allowing 12 different source configurations.

Figure 1: Washing machine on concrete base with rubber feet

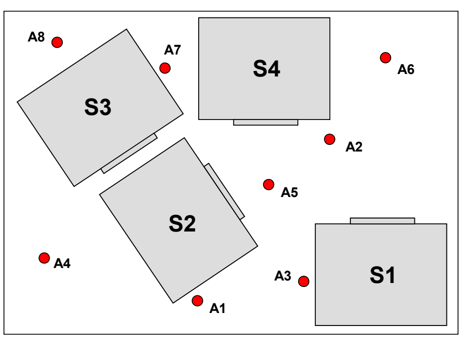

Figure 2: Source and accelerometer positions on the RP

Both sources are first placed on a RP to determine their characteristic RP power level. The RP is a 280 x 200 x 10 cm³ reinforced concrete plate mounted on its edges on thick resilient strips in order to obtain a minimum total loss factor of 8 % up to 100 Hz. Hence, it complies with the specifications given in EN 15657-1. For all source combinations, the RP-averaged velocity level is measured for 4 source positions and 8 accelerometer positions randomly distributed over the RP (see Figure 2). The input mobility of the RP is measured in 117 points on a regular grid with grid size of 20 cm.

Secondly, both sources are moved to a 16 cm thick reinforced concrete floor of a standard impact sound test cell, representing a simple building structure (floor 1 in Figure 3). The walls of this test suite are made of 19 cm thick hollow concrete bricks, filled with sand. Wall 7 is made of a gypsum board glued to 8 cm thick gypsum blocks. Walls 3, 6 and 8 have door openings. Ceiling 9 is identical to floor 1. The foundation base of the test suite is a very thick concrete slab, vibrationally isolated from its surroundings. For all source combinations, the averaged velocity level is measured for 4 source positions and 7 accelerometer positions randomly distributed over the floor (see Figure 4). Simultaneously, the space-averaged sound pressure level is measured in the lower cell. The input mobility of the floor is measured in the contact points for the washing machine. Finally, the reverberation time of the lower cell is measured.

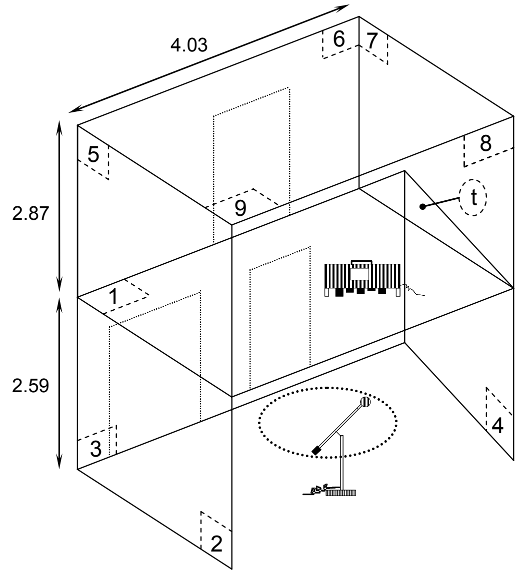

Figure 3: Test suite, representing the in-situ building structure

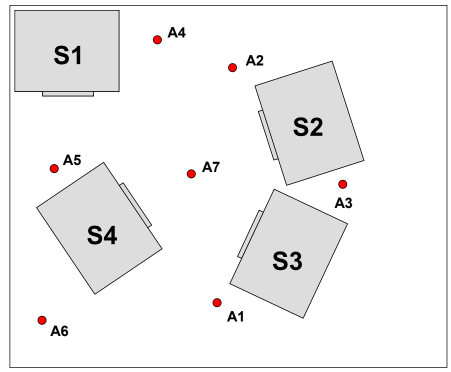

Figure 4: Source and accelerometer positions on the floor

3. PREDICTION MODEL

For each source configuration, the structure-borne sound pressure level in the lower cell can be estimated using the prediction model in EN 12354-5:

$$L_s = 10\,lg \sum_{j=1}^{4} 10^{L_{s,ij}/10} . \tag{1}$$

For the direct path, the contribution $L_{S,ij}$ is given by:

$$L_{s,Dd} = L_{w,inst,1} - D_{sa,1} - R_1 - 10\,lg\left(A_r/4\right), \tag{2}$$

with $L_{W,inst,1}$ the sound power level, injected in the floor, R_1 the sound reduction index of the floor, according to EN 12354-1, Annex B.1 (considering free and forced transmission), $D_{sa,1}$ the adjustment term for structure-borne to airborne excitation and A_r the equivalent absorption area of the lower cell, estimated from the measured reverberation time using Sabine's formula.
For the flanking paths, the contributions $L_{S,ij}$ are given by:

$$L_{s,Df} = L_{w,inst,1} - D_{sa,1} - R_{1f} - 10\,lg\left(A_r/4\right), \qquad \text{with } f = 2, 3, 4. \tag{3}$$

1. The installed structure-borne sound power level is predicted from the characteristic reception plate power $L_{Wsn,rec}$ and the ratio of the averaged real parts of the input mobilities of the floor at the contact points with a characteristic RP mobility according to EN 15657-1:

$$L_{Ws,inst,1} = L_{Wsn,rec} + 10\,lg\left(\overline{Re\left\{Y_{b,1}\right\}}/Y_{\infty,rec}\right) \tag{4}$$

The characteristic reception plate power $L_{Wsn,rec}$ is calculated from the measured injected sound power level in the RP:

$$L_{Wsn,rec} = L_{Ws,rec} + 10\,lg\left(Y_{\infty,rec} / Re\{Y_{rec}\}\right). \tag{5}$$

Here, the real parts of the input mobilities at the contact points are linearly interpolated from the real parts of the input mobilities on the measured grid of mobilities.

2. The adjustment term for structure-borne to airborne excitation of the floor $D_{sa,1}$ is given by EN 12354-5:

$$D_{sa,1} = 10\,lg\frac{2\pi m_1 2.2\tau_{1,res}}{\rho_0 c_0 T_{s,1,situ}\sigma_{1,res}} \tag{6}$$

with $\tau_{1,res}$ the resonant transmission coefficient and $\sigma_{1,res}$ the resonant radiation factor according to EN 12354-1, annex B.1, $T_{s,1,situ} = 2.2/f\eta_{tot,1}$ the structural reverberation time with $\eta_{tot,1}$ the loss factor according to EN 12354-1, annex C (field situation). To determine these quantities, the triangular part of floor 1 was neglected as it is separated from the main part of floor 1 by wall 7 (see Figure 3).

3. The flanking sound reduction indices R_{1f} (f = 2, 3, 4) can be predicted using EN 12354-1:

$$R_{1f} = \frac{R_{1,res,situ} + R_{f,res,situ}}{2} + \overline{D_{v,1f,situ}} + 10\,lg\left(\frac{S_1}{\sqrt{S_1 S_f}}\right). \tag{7}$$

with

- $R_{i,res,situ}$ the field resonant sound reduction index of building element i:

$$R_{i,res,situ} = R_{i,res} - 10\,lg\frac{T_{s,i,situ}}{T_{s,i,lab}} \quad , \ i = 1, f \tag{8}$$

  where $R_{i,res}$ is the sound reduction index according to EN 12354-1, annex A, considering only resonant transmission and $T_{s,i,situ}$ and $T_{s,i,lab}$ according to EN 12354-1, annex C (field situation and lab situation respectively) and
- $\overline{D_{v,1f,situ}}$ the direction-averaged velocity level difference between element 1 and element *f* in the field situation:
  - For f = 2, 3, $\overline{D_{v,1f,situ}}$ can be written as:

$$\overline{D_{v,1f,situ}} = K_{1f} - 10\,lg\left(\frac{l_{1f}}{\sqrt{a_{1,situ} a_{f,situ}}}\right), \tag{9}$$

    with
    - K_{1f} the vibration reduction index of the transmission path $1 - f$, according to EN 12354-1, annex E;
    - $l_{1,f}$ the coupling length of the common junction between the floor and element f and

- $a_{i,situ}$ the equivalent absorption length of element i in the actual field situation, given in EN 12354-1:

$$a_{i,situ} = \frac{2.2\pi^2 S_i}{c_0 T_{s,i,situ}} \sqrt{\frac{f_{ref}}{f}} \quad , \; i = 1, f \; , \tag{10}$$

where f_{ref} = 1000 Hz and S_i is the area of surface i.

- For f = 4, the flanking sound reduction index R_{1f} is determined by two junctions. The direction-averaged velocity level difference $\overline{D_{v,1,4,situ}}$ can be predicted using EN 12354-5, Annex F.1:

$$\begin{aligned} \overline{D_{v,1,4,situ}} &= K_{1f} - 10\,lg \frac{\sqrt{l_{1t} l_{t4}}}{\sqrt{a_{1,situ} a_{4,situ}}} \\ K_{1,4} &= K_{1t} + K_{t4} - 10\,lg\left(\sqrt{l_{1t} l_{t4}} \frac{1}{a_{t,situ}} \right) - \Delta K \end{aligned} \quad , \tag{11}$$

with

- t the triangular part of floor 1 (see Figure 3) and
- $\Delta K = 4$ dB for two junctions, which is the adjustment term for the vibration reduction index to take into account a reduced reduction due to wave types other than bending waves.

4. MEASUREMENTS AND ANALYSES

Since the measurement of the injected sound power level in the RP becomes less accurate for low eigenmode densities and because the calculated quantities in the annexes of EN 12354-1 are based on SEA, assuming high eigenmode densities, the minimum frequency considered in this paper is 100 Hz.

A. Averaged real part of receiver mobility

In Figure 5, the average of the real parts of input mobilities at the contact points of position S4 on the reception plate is compared with the average of the real parts of input mobilities at the contact points of position S3 on floor 1 in the building structure. The mobility of a characteristic reception plate is also plotted. If a source has a mobility that is much larger than the mobility of the reception plate for all frequencies, the source will behave as a so-called "force source" and the RPM of equation (5) will be valid. In this case, it is clear from the figure that the source will also behave as a force source on floor 1 in the building structure, allowing equation (4) to be applied.

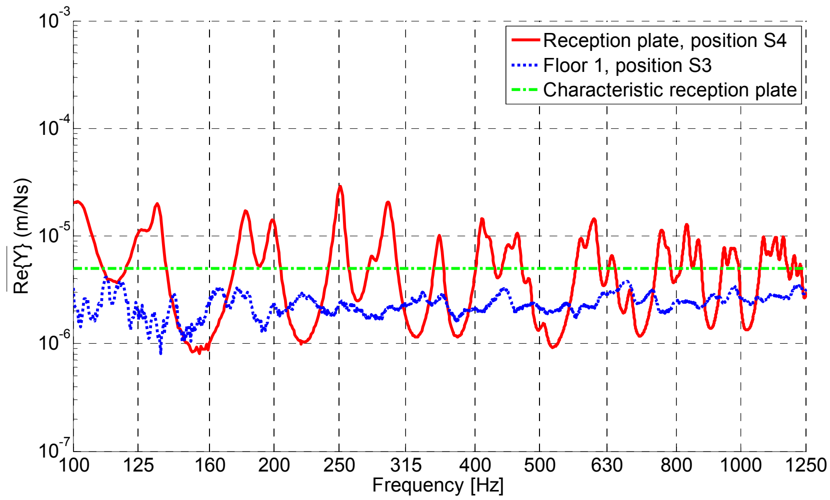

Figure 5: Averaged real parts of input mobilities at the contact points for source position S4 on the reception plate and at the contact points for source position S3 on floor 1 in the building structure, compared to the mobility of a characteristic reception plate.

B. Comparison of measured sound pressure level and calculated sound pressure level from $L_{W,inst,1}$

The sound pressure level in the lower cell doesn't vary greatly when a source is put on different positions on floor 1 of the building structure, due to the fact that the floor mobility isn't very dependent on the location of the contact points. Therefore, for all following sound pressure levels, a source position-averaged value will be shown.

ISO tapping machine

In Figure 6, a comparison is made between the measured and calculated sound pressure level from $L_{W,inst,1}$ in the lower cell of the building structure with the ISO tapping machine on floor 1.

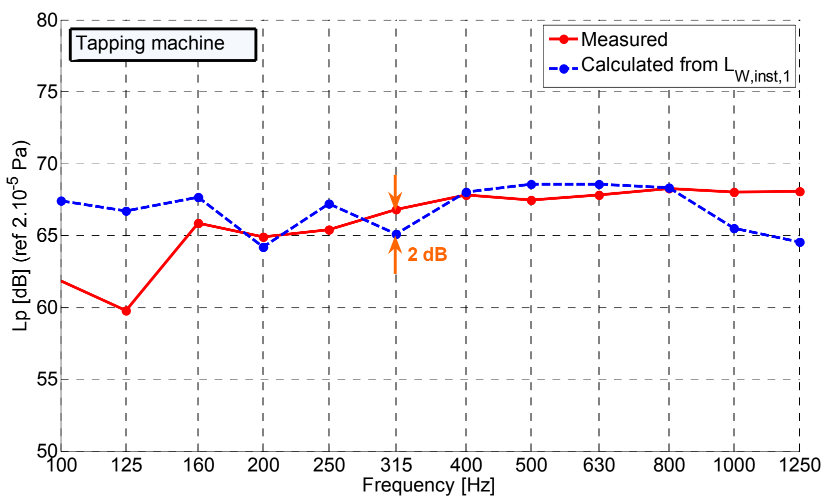

Figure 6: Comparison of the source position-averaged measured sound pressure level and the source position-averaged calculated sound pressure level from $L_{W,inst,1}$ in the lower cell of the building structure with an ISO tapping machine on floor 1.

The results are very promising. Only in the lower frequency bands of 100 Hz and 125 Hz the deviation between measurement and calculation exceeds 5 dB. In most other bands, the deviation is smaller than 2 dB. This means not only that the RPM works well with this broadband source, but also that the calculation EN 12354-5 is based on well estimated quantities by EN 12354-1. From 125 Hz and lower, the RPM and/or the estimation of quantities are less reliable.

Washing machine

In Figure 7, an analogue comparison as in Figure 6 is shown, but for the washing machine as a source on different mountings and for various operating frequencies.

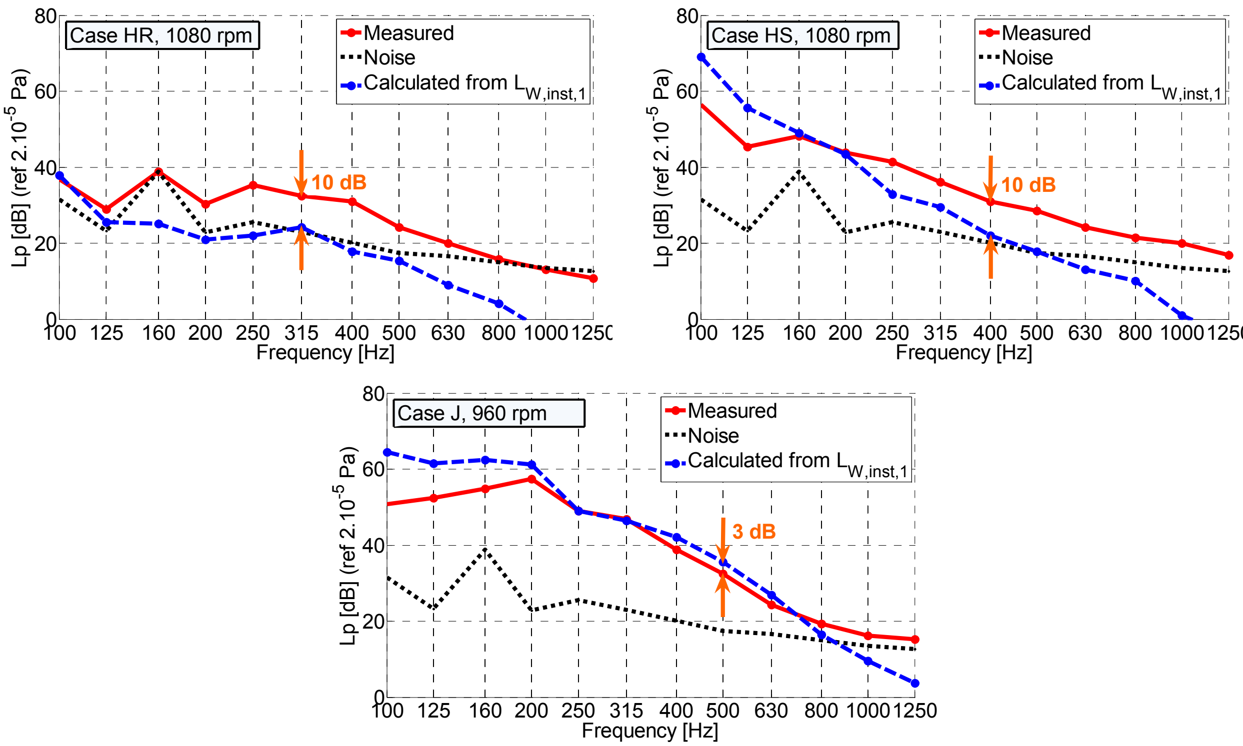

Figure 7: Comparison of the source position-averaged measured sound pressure level and the source position-averaged calculated sound pressure level from $L_{W,inst,1}$ in the lower cell of the building structure with the washing machine on different mounting and with various operating frequencies on floor 1.

For the mounting case with the concrete base supported by rubber feet (case HR), the calculation is underestimating the measured sound pressure level. This underestimation is thought to be caused by a dominating airborne component in the total sound pressure level in the lower cell. However, this component has not been estimated. Above 500 Hz, noise is governing the measured sound pressure level. Therefore, no comparison can be made with the calculation. It can also be mentioned that this way of mounting is a qualitatively very good measure to lower structure-borne sound transmission, since the recorded sound level spectrum is extremely low.

The comparison between measured and calculated sound pressure levels for case HS, with steel feet instead of rubber feet, is not very good. The spectral behavior is different, since the blue curve is steeper than the red curve. The reason for the bad agreement is probably the invalidity of the force source assumption, on which the RPM is based. The source mobility is, with the hard steel feet and the heavy concrete base, getting close to or even being less than the RP mobility.

Case J, where the concrete base is shortcut by jacks, gives excellent analogy between measurement and calculation with deviations below 3 dB. Like the case with the ISO tapping machine as the source, there are only larger deviations for the lower frequency bands of 100 Hz, up to 160 Hz. For both source combinations, these differences may be caused by the limited eigenmode density on the RP and/or a less accurate estimation of parameters by the annexes in EN 12354-1.

5. CONCLUSIONS

The Reception Plate Method (RPM) and the prediction model in EN 12354-5 are used to estimate the structure-borne sound pressure level in the lower room of a simple building structure. An ISO tapping machine and a washing machine with different mountings and operating frequencies are used as a source on the floor of the upper room. The sound pressure level in the lower cell is measured to validate the RPM and EN 12354-5, the latter of which uses estimations of building properties outlined in the annexes of EN 12354-1.

The promising results with the ISO tapping machine show that the RPM assumptions are valid with this broadband source and that the model parameters in EN 12354-5 are well estimated by the annexes in EN 12354-1. Only for lower frequency bands, there are larger deviations between predictions and measurements. These might be due to limited eigenmode density on the reception plate and/or less accurate estimations of model parameters by EN 12354-1.

The results for the washing machine depend on the mounting. For a mounting with a heavy concrete base on rubber feet, the sound pressure level is probably dominated by airborne sound transmission and therefore no conclusions can be made about the prediction of the structure-borne sound transmission. In practice, it is evident that, in these cases, the airborne radiation needs to be addressed first in order to further reduce sound transmission of service equipment. When the rubber feet are replaced by steel feet, the sound pressure level is higher but is not well predicted. In this case however, the source mobility approaches the mobility of the receiver, while the RPM assumes high mobility sources on low mobility receivers.

If the concrete base is shortcut by jacks as supports, the agreement between prediction and measurement is comparable with the ISO tapping machine case, suggesting that the RPM can also be used for low-frequent tonal force sources.

To further clarify the above mentioned discrepancies, the authors intend to verify most of the calculation steps by systematically measuring the estimated intermediate quantities.

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REFERENCES

[1] EN 15657-1:2009 *Acoustic properties of building elements and of buildings - Laboratory measurement of airborne and structure borne sound from building equipment - Part 1: Simplified cases where the equipment mobilities are much higher than the receiver mobilities, taking whirlpool baths as an example*.

[2] EN 12354-5:2009 *Building acoustics - Estimation of acoustic performance of building from the performance of elements - Part 5: Sounds levels due to the service equipment*.

[3] EN 12354-1:2000 *Building Acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 1: Airborne sound insulation between rooms*.