# Playing ball with transients on the force plate and on the reception plate 

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#### Abstract

The popularity of the reception plate method (RPM) to characterize structureborne sound sources in buildings is growing worldwide. The source properties obtained from the RPM (blocked force and/or characteristic power) can be used as input data for the prediction of the sound power ( $L_{e q}$ ) radiated into nearby rooms in heavy, homogeneous constructions.

Much experience has already been obtained for steady-state structure-borne sound sources whose impedance is much lower than that of the reception plate. However, experience is lacking for sources with transient excitation characteristics. One complicating factor for the assessment of transient signals is that a different metric, $L_{A, F, \text { max }}$, is used (e.g. in building regulations), for such signals because it correlates best with annoyance perceived by building occupants.

In this paper the well-characterized standardized heavy-soft impact source (also known as Tachibana ball) is investigated on the reception plate. Measurements performed on the reception plate are compared to blocked force measurements on a force plate. The influence of the structural reverberation time of the reception plate on the $L_{A, F, \max }$ is investigated among other things.


Keywords: Impact Noise, Reception Plate, Transient Excitation, Heavy Soft Impact
Source
I-INCE Classification of Subject Number: 51, 72

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## 1. INTRODUCTION

More and more often the reception plate method (RPM) is used to capture input data needed for the prediction of sound power radiated from structure-borne sound sources with steady-state excitation characteristics into nearby rooms in heavy homogeneous construction using ISO 12354-5 [1]. Several prediction studies show that when using steady-state structure-borne excitation and quasi-steady-state excitation, e.g.for a shower basin excited by a standardized water stream [2] and air-conditioning units [3], the results are reliable. However, few studies have been carried out with transient structure-borne excitation.

In recent research [4] an empirical correction was developed to obtain $L_{F, \max }$ from $\max \left\{L_{\text {eq }}, 125 \mathrm{~ms}\right\}$ for transient signals. The correction gave very promising results for artificially generated transient idealized time-varying signal that were used to excite a floor via a shaker and while measuring the sound pressure levels $\max \left\{L_{e q}, 125 \mathrm{~ms}\right\}$ and $L_{F, \max }$ in the receiving room below.

This short pilot study differs in two ways from the above described research study. First, instead of investigating results obtained from artificially generated transients, a truly transient source was employed and second, a correction was found not between the sound pressure levels max $\left\{L_{e q}, 125 \mathrm{~ms}\right\}$ and $L_{F, \text { max }}$ but between the A-weighted Maximum FastWeighted Velocity Level, $L_{v, A F, \text { max }}$ and the Peak Velocity Level, $L_{v, A, p e a k}$.

The standard rubber ball was chosen as excitation source as it is a well-investigated transient source common to the building acoustics community. Predictions of the blocked force of the rubber ball were made by Schoenwald [5] and the influence of the reverberation times in the receiving room on the fast-weighted impact sound pressure level are also known [6].

Furthermore, the impact force exposure level $L_{F E}$ is here compared for different drop heights on two differing measurement setups, the Reception Plate (RP) and the Force Plate (FP).

## 2. MEASUREMENT SETUP

The standard rubber ball (also known as Tachibana ball), described in ISO 10140-5 [7], was used on both the reception plate and the force plate. The ball was repeatedly dropped onto the plates from different heights, and the time-dependent force or velocity responses of the plates were recorded. The measurement setup for both cases is described in this section. Signal post-processing and analysis are discussed in Section 3.

### 2.1. Force Plate (FP)

The measurement setup for this part of the study is described in more detail in [5]. In brief, the measurements were carried out on a Type FP-10 force plate from RION. The force plate was placed on a rigid concrete floor, with a thin sheet of vinyl covering (see Figure 1). The standard rubber ball was dropped from 16 different heights ( 10 cm to 160 cm ), with five repeats per drop height, resulting in 80 measurements.

### 2.2. Reception Plate (RP)

The HFT Stuttgart reception plate test rig (see Figure 2) was used for this part of the study. The standard rubber ball was dropped on one of three plates in the test rig,


Figure 1: Force plate (left) and ball drop tests (right)
the horizontal reception plate. This plate has a thickness of 10 cm and dimensions of $200 \mathrm{~cm} \times 280 \mathrm{~cm}$. A more detailed description can be found in [8].


Figure 2: Reception plate test rig at HFT Stuttgart, without (left) and with operator (right)
The rubber ball was dropped at three locations from three different heights $(50 \mathrm{~cm}$, 100 cm , and 150 cm ), with three repeats each resulting in 27 measurements. The resulting time-dependent velocity on the RP was captured at nine positions per drop.

The operator, dropping the ball onto the reception plate, was "decoupled" from the reception plate by elastomer pads. The influence of the operator on the results was investigated by dropping the ball on the RP with and without the operator standing on the RP and was found to be negligible.

## 3. ANALYSIS

### 3.1. Force Plate (FP)

The force signals that are used in the following analysis were measured directly on the force plate, without the need for indirect calculations. The force plate is equipped with three force transducers. The transducers were calibrated before the measurements. The time signals from the three transducers were added to obtain the force time signal for each ball drop. Each signal was captured for 10 s , with a sampling rate of 44.1 kHz . In
post-processing, a 1 s time signal was extracted from each recorded time signal, using a rectangular time window. The time signals from the five repeated drops per drop height were averaged to obtain a single force time signal for each drop height.

### 3.2. Reception Plate (RP)

Direct measurement of the force signals on the reception plate is impossible without the insertion of a force transducer at the source-receiver interface. For this reason, the forces between rubber ball and reception plate had to be determined indirectly. One way to perform such inverse calculations is by way of measuring the transfer paths between the source-receiver interface and remote response positions, and subsequent inverse calculations of the force from measured velocity signals. In this study, a different approach was examined.

The force signals on the reception plate were estimated from the reception plate power $P$. For a high-mobility single-contact, single-degree of freedom source on a low-mobility receiver, the power injected by the source into the receiver is a function of receiver mobility $Y_{\text {rec }}$ and blocked force of the source $F_{b}$ :

$$
\begin{equation*}
P=Y_{r e c} \cdot F_{b}^{2} \tag{1}
\end{equation*}
$$

For the concrete reception plate used in this study, the injected power can also be estimated from the kinetic energy of the plate and its loss factor $\eta$. The kinetic energy of the plate is determined through measurement of the spatially-averaged squared velocity on the plate and the plate mass. This yields the well-known equation for the reception plate power $P$ :

$$
\begin{equation*}
P=m \cdot\left\langle v^{2}\right\rangle \cdot \eta \tag{2}
\end{equation*}
$$

Combining Equations 1 and 2 and solving for $F_{b}$ allows the estimation of the blocked force from measured velocity signals, receiver mobility, and plate loss factor:

$$
\begin{equation*}
F_{b} \approx \sqrt{\frac{P}{Y_{r e c}}}=\sqrt{\frac{m \cdot\left\langle v^{2}\right\rangle \cdot \eta}{Y_{r e c}}} \tag{3}
\end{equation*}
$$

It should be stressed that Equation 3 contains multiple assumptions and various sources of measurement uncertainties, e. g. high-mobility source assumption, assumption of linearity of source and receiver, uncertainty due to loss factor determination and interpolation, uncertainty due to sampling errors of the plate vibration field, etc.

The calculations described above must be performed in the frequency domain. An inverse FFT is required to finally obtain a time signal for the transient blocked force. The following steps were taken to calculate the force time signals for the reception plate data: The measured velocity signals on the reception plate were transformed to the frequency domain (FFT). The plate loss factor, measured in one-third octave bands, was interpolated using a piecewise cubic spline interpolation with the same frequency resolution as the narrowband velocity signals. The receiver mobility was also only available in one-third octave bands and therefore had to be interpolated as well. This is a potentially significant source of error, as the receiver mobility can vary quite broadly (depending on the damping of the plate). The reception plate power was then calculated in narrowband spectra using Equation 2. From this, the blocked force of the rubber ball was estimated using Equation 3. The resulting force spectra was finally transformed back into the time domain (inverse FFT).

### 3.3. Parameters

From the measured and/or estimated force and velocity time signals, several parameters were determined.

### 3.3.1 Impact force exposure level $L_{F E}$

The impact force exposure level $L_{F E}$ was calculated from the force signals according to ISO 10140-5 [7]:

$$
\begin{equation*}
L_{F E}=10 \log _{10}\left(\frac{1}{T_{0}} \int_{t_{1}}^{t_{2}} \frac{F^{2}(t)}{F_{0}^{2}} d t\right) \tag{4}
\end{equation*}
$$

Following the standard, $L_{F E}$ was evaluated in octave bands between 31.5 Hz and 500 Hz .

### 3.3.2 Peak velocity level $L_{v, A, p e a k}$

The peak velocity level $L_{v, A, p e a k}$ was calculated as the maximum level of the Aweighted velocities. The A-weighting was applied to the measured velocity signals in the frequency domain (filter coefficients according to IEC 61672). Afterwards, the signals were band-filtered in octave or one-third octave bands. No time-weighting was applied.

### 3.3.3 Maximum FAST-weighted velocity level $L_{v, A F, \max }$

The maximum FAST-weighted velocity level $L_{v, A F, \max }$ was calculated as the maximum level of the A-weighted, FAST-weighted velocities. The basic calculation was the same as for the peak velocity level $L_{v, A, p e a k}$, but at the very end an exponential window with a time constant of ( $\tau=0.125 \mathrm{~s}$, FAST) was applied to the signal.

## 4. RESULTS

### 4.1. Time Signals

Figures 3 a and 3 b show some of the force and velocity time signals that were measured on the force plate and the reception plate. While a direct comparison between the two plots is not possible (because one shows forces and the other velocities), it is nevertheless apparent that the response is longer on the reception plate (note that the two plots show the same signal length).

(a) Force time signals on force plate

(b) Velocity signals on reception plate

### 4.2. Impact force exposure level $L_{F E}$

The impact force exposure level $L_{F E}$ was calculated from the force signals according to Equation 4. Figure 4a shows the impact force exposure level on the force plate, for three different drop heights: $50 \mathrm{~cm}, 100 \mathrm{~cm}$, and $150 \mathrm{~cm} . L_{F E}$ is a function of frequency, with higher values at low frequencies and decreasing values with increasing frequency. The rubber ball was designed to excite primarily low frequencies below 100 Hz . It serves its purpose, as confirmed in Figure 4a.

Figure 4 b shows the impact force exposure level on the reception plate, at one of the three excitation positions and for the three drop heights of $50 \mathrm{~cm}, 100 \mathrm{~cm}$, and 150 cm . It is immediately obvious that $L_{F E}$ on the reception plate has the same "shape" as $L_{F E}$ on the force plate. In addition, the relative differences between the $L_{F E}$ values for different drop heights seem to agree quite well between the two plates. This was investigated further, and the results are shown for two of the three excitation positions in Figure 5.

Each figure shows the relative differences between drop heights of 100 cm or 150 cm , compared with a drop height of 50 cm on the same plate (force plate or reception plate). The agreement for excitation position 1 is remarkably good, with only small deviations at high frequencies. The agreement for excitation position 2 is not quite as good (some larger deviations for 150 cm ), though the results are still within 2 dB . (The agreement for excitation position 3 (not shown) is slightly better than for excitation position 2.)


Figure 4: Impact force exposure level $L_{F E}$


Figure 5: Relative differences between different drop heights in impact force exposure level, for the force plate and the reception plate. The reference in each case is a drop height of 50 cm .

Based on these findings, it appears that the rubber ball behaves very similar on the reception plate and on the force plate, and that the frequency contents of the force
excitation spectra in both cases agree quite well with each other. The fact that the relative differences between the impact force exposure levels agree closely supports the assumption that the force signal on the reception plate can, in principle, be calculated from the measured velocity signals and reception plate power. However, the force time signals that were determined from this spectrum were not plausible. This was likely due to signal processing issues and the assumptions and simplifications that were used in the calculations. Specifically, the phase of the receiver mobility, not addressed here, is an important piece in the puzzle to estimate the blocked force time signal. This is a topic of further investigation.

### 4.3. Maximum FAST-weighted velocity level versus peak velocity level $L_{v, A F, \text { max }}$ VS. $L_{v, A, p e a k}$

Figure 6 shows the A-weighted maximum FAST-weighted velocity level, $L_{v, A F, \max }$ and A-weighted peak velocity level $L_{v, A, p e a k}$ captured from ball drops at three different heights ( $50 \mathrm{~cm}, 100 \mathrm{~cm}$, and 150 cm ) and at three different drop positions. Notice that the linear time-weighted signals, $L_{v, A, p e a k}$, are always higher than the FAST-weighted signals, $L_{v, A F, \max }$. Transformed into force levels, using Equation 3, yields the same deviations, which are caused by the convolution of the decaying reverberant velocity field on the RP and the FAST-weighted decay curve.


Figure 6: Spatially-averaged velocity level $L_{v}$ on Reception Plate time-weighted linearly ( $L_{v, A, \text { peak }}$ ) and exponentially ( $L_{v, A F, \max }$ ) with a reference velocity of $v_{0}=5 \times 10^{-8} \mathrm{~m} / \mathrm{s}$ for the three different drop heights and drop positions.

To correct for this phenomena, the same approach is used as by Schoenwald [6] for airborne noise, in which the room response (reverberation time) had influence on the maximum FAST-weighted sound pressure levels. However, in the current study the structural reverberation times are used. The correction is calculated analytically, assuming an ideal impulse is convoluted with the FAST-weighted decay curve, and written as:

$$
\begin{equation*}
\Delta L_{v, F, \text { max }}=10 \log \frac{v_{F, \text { max }}^{2}}{v_{p e a k}^{2}}=10 \log \left[\frac{1}{1-C_{T}^{-1}}\left(C_{T}^{\left(1-C_{T}\right)^{-1}}-C_{T}^{-\left(1-C_{T}^{-1}\right)^{-1}}\right)\right] \tag{5}
\end{equation*}
$$

where $C_{T}=T_{60} / 1.7275$, with $T_{60}$ being the structural reverberation time of the RP. Both the structural reverberation times of the RP $T_{60}$ and the correction $\Delta L_{v, F, \max }$ are shown in Figure 7.


Figure 7: Correction $\Delta L_{v, F, \text { max }}$ over structural reverb time of $R P T_{60}$ (left) and structural reverb time of RP over frequency (right)

Figure 8 shows the difference between $L_{v, A F, \text { max }}$ and $L_{v, A, p e a k}$ as well as the correction term calculated according to Equation 5.


Figure 8: Difference of spatially-averaged velocity level on Reception Plate timeweighted linearly ( $L_{v, A, p e a k}$ ) and exponentially ( $L_{v, A F, \text { max }}$ ) and correction term calculated according to Equation 5 for the three different drop heights and drop positions.

The study by Schoenwald using airborne noise showed that reverberation times in the receiving room above 1 s lead to variations in the maximum FAST-weighted sound
pressure level of up to 3 dB . However, for reverberation times below 1 s the difference between the two signals can vary by more than 10 dB . In this study the variations were between 9 dB and 14 dB . The differences between the correction and measurements (see Figure 8) lie with $\pm 3 \mathrm{~dB}$, which is believed to be rather good given the many assumptions in the calculations.

As the reception plates have short structural reverberation times [4] the influence of FAST weighting on the RP velocity levels should be addressed when predicting FASTweighted sound pressure levels in adjacent receiving rooms.

## 5. SUMMARY AND CONCLUSION

A first step was taken to investigate a transient structure-borne sound source, the standardized rubber ball, on the reception plate. The relative difference of impact force exposure levels for different drop heights on the reception plate and force plate give comparable results. It was shown that an analytical correction can be used to calculate the maximum FAST-weighted velocity levels from the peak velocity levels and vice versa with an error of $\pm 3 \mathrm{~dB}$.

In the next steps, the influence of the phase of the receiver mobility will be looked at closer. Furthermore, these all findings will be applied and validated for a full prediction of the maximum FAST-weighted sound pressure levels in an adjacent room caused by the ball drop utilizing reception plate data based on ISO 12354-5.

## ACKNOWLEDGMENT

The authors would like to acknowledge and thank Steffi Reinhold, PhD student at the University of Liverpool and currently working at the University of Applied Sciences Stuttgart (HFT), for providing the material properties of the reception plate and for coordinating the ball drop measurements on the reception plate.

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