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FORCE-BASED TRANSFER FUNCTIONS FOR FORCE-SOURCE CONDITIONS – WHERE SIMPLIFICATION PAYS OFF

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Abstract

Predicting structure-borne sound from building service equipment (BSE) in heavyweight buildings according to EN 12354-5 requires the normalised impact sound pressure level (SPL) of the floor or wall carrying the equipment. For floors it is measured with a standard tapping machine, whose hammers cannot fall sideways, so the method cannot be applied to walls. EN 17823 therefore determines it indirectly, from complex narrowband transfer functions of EN ISO 10848-1; Annex C of EN 15657 and EN 14366-1 apply the same principle to BSE and waste water systems. This contribution shows that, where a force-source condition applies – as is typical in heavyweight construction – the detour via the injected power is unnecessary: the receiver mobility needed to convert force into power and back cancels out. The normalised impact SPL then follows from the force levels of the calibration source and tapping machine and from the sound pressure level in the receiving room, all measurable in third-octave bands. In narrow bands both formulations are mathematically equivalent; in third-octave bands the force-based one avoids a systematic error from the inconsistent band averaging of the mobility in EN 15657. Amendments to EN ISO 10848-1, EN 17823, EN 15657 and EN 14366-1 are proposed.

Keywords: *impact sound pressure level, transfer function, force-source condition*

1. Introduction

Structure-borne sound from building service equipment (BSE) – for instance from the water-carrying pipes of fresh and waste water systems – can be disturbing for building occupants. Driven by the flowing water, such pipes act as active structure-borne sound sources that excite the building structure through the pipe clamps; the resulting vibration is radiated as airborne sound into rooms in need of protection.

For the prediction of the normalised sound pressure level (SPL) $L'_{n,BSE}$ due to BSE in heavyweight construction according to EN 12354-5 [1], the normalised impact SPL is required as an input quantity:

$$L'_{n,BSE} = L'_{n,i} + L_{Fb,eq} - L_{Fb,eq,stm} \tag{1}$$

Here $L'_{n,i}$ is the normalised impact SPL of element i, and $L_{Fb,eq}$ and $L_{Fb,eq,stm}$ are the equivalent blocked force levels of the BSE and of the standard tapping machine (stm). The test procedure for determining the blocked force of a waste water system according to EN 14366-1 [2] is described in detail in [3].

For BSE mounted on walls, the prediction according to EN 12354-5 requires the normalised impact SPL of the wall. Since its hammers fall under gravity, the standard tapping machine can only be used on horizontal surfaces, so a direct measurement of the normalised wall impact SPL is not possible. In [4] an alternative method for determining the normalised impact SPL by means of transfer functions was investigated and validated, and the results were compared with direct measurements using a mechanical pendulum tapping machine and an electrodynamic tapping machine.

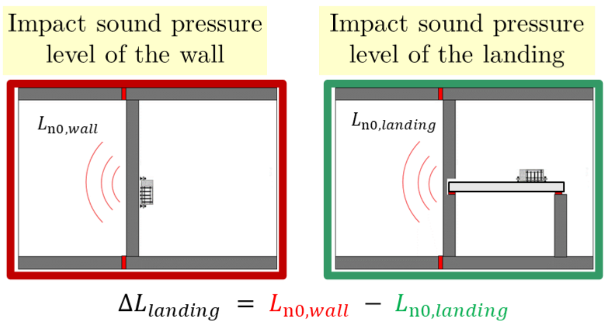

Figure 1. Determination of the impact sound reduction of an isolated stair landing according to EN 17823 from the normalised impact SPLs of wall and landing.

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The method presented in [4] has been implemented normatively in EN 17823 [5]. Fig. 1 shows the principle used in EN 17823 for determining the impact sound reduction of isolating elements of heavy stair landings: the normalised impact SPL is determined both for the wall and for the stair landing supported in the wall on isolating elements. The difference between the two yields the impact sound reduction of the isolated landing, analogously to floating floors on floor slabs.
The indirect determination of the normalised impact SPL is based on the building transfer function of EN ISO 10848-1 [6], measured in the building-like test facility shown in Fig. 2. It describes the ratio of the mean square sound pressure $\langle \tilde{p}_{\mathrm{cal}}^2 \rangle$ in the receiving room to the structure-borne sound power W_{cal} injected by a calibration source (index: cal):

$$D_{\mathrm{TF}} = 10 \log_{10} \left(\frac{\langle \tilde{p}_{\mathrm{cal}}^2 \rangle}{W_{\mathrm{cal}}} \frac{W_0}{p_0^2} \right) = L_{\mathrm{p,cal}} - L_{\mathrm{W,cal}} \qquad (2)$$

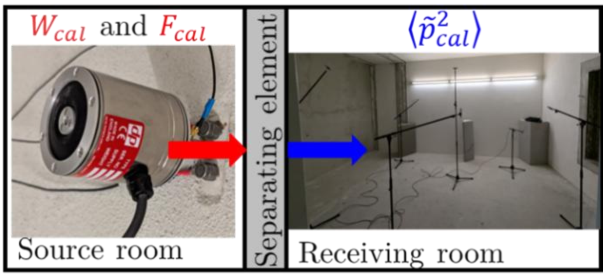

Figure 2. Determination of the transfer function in the building-like test facility – excitation of the separating wall by a shaker while the excitation force, the velocity at the contact point and the sound pressure in the receiving room are measured simultaneously.

A closely related transfer function approach is given in Annex C of EN 15657 [7] for the characterisation of BSE and forms the basis of EN 14366-1 [2] for waste water systems. There, the power installed in the receiving element and the resulting velocity of that element are linked by the power substitution method. Here too the decisive criterion is the force-source condition, which piping systems installed on massive building elements typically fulfil.
The present contribution shows that, for a force-source condition, this procedure can be reduced to a simpler method based on a direct force comparison, because the receiver mobility cancels out completely. The consequences for the standards concerned are discussed.

2. Impact sound pressure level from transfer functions

According to EN 17823, the normalised impact SPL can be determined from the building transfer function D_{TF} of EN ISO 10848-1 and from the installed power $L_{\mathrm{W,stm}}$ of the standard tapping machine [5]:

$$L'_{\mathrm{n}} = D_{\mathrm{TF}} + L_{\mathrm{W,stm}} + 10 \log_{10} \left(\frac{A}{A_0} \right) \qquad (3)$$

The transfer function D_{TF} is determined from the cross spectrum of the force F_{cal} and the resulting velocity v_{cal} at the contact point together with the sound pressure p_{cal} in the receiving room, see Fig. 2. Since both the power and the sound pressure have to be acquired with narrowband resolution and then converted into third-octave band levels, complex-valued measurement data and considerable post-processing effort are required.
The decisive prerequisite for the following is a force-source condition at the contact point: the receiver mobility of the element to which the BSE is attached is much smaller than the source mobility ($Y_{\mathrm{R}} \ll Y_{\mathrm{S}}$) of the BSE. The contact force then corresponds approximately to the blocked force of the BSE. This is a property of the source–receiver pair, not of the construction as such; in heavyweight construction it is usually, but not necessarily, fulfilled. Under this assumption the installed power of the tapping machine can be calculated from the force spectrum of its blocked force $F_{\mathrm{b,stm}}$ and the real part of the receiver mobility Y_{R}:

$$W_{\mathrm{stm}} = \tilde{F}_{\mathrm{b,stm}}^2 \mathrm{Re}\{Y_{\mathrm{R}}\}$$
$$L_{\mathrm{W,stm}} = L_{\mathrm{Fb,eq,stm}} + 10 \cdot \log_{10}(\mathrm{Re}\{Y_{\mathrm{R}}\}/Y_0) \qquad (4)$$

The receiver mobility is determined with narrowband resolution according to ISO 7626-1 [8] from the cross spectrum of velocity and force at the contact point and the auto spectrum of the force, and is then converted into third-octave bands as defined in EN 15657, see Eq. (11) below.
Whether a force-source condition is fulfilled therefore has to be verified in each case by comparing the source mobility of the source under consideration with the receiver mobility. For the calcium silicate separating walls of the building-like test facility and of the stair test facility, with thicknesses of 11.5 cm (EN 14366-1) and 24 cm (EN 17823), the characteristic mobility of an infinite plate according to Eq. (5) can be assumed approximately, with the bending stiffness B and the mass per unit area m' of the plate [7]:

$$Y_\infty = \frac{1}{8\sqrt{m' \cdot B}} \qquad (5)$$

The mobility of a single hammer of the tapping machine with a mass of $m = 0.5\,\mathrm{kg}$ can be approximated by the mass mobility according to Eq. (6).

$$Y_{\mathrm{m}} = \frac{1}{j\omega m} \qquad (6)$$

As can be seen in Fig. 3, a force-source condition is fulfilled for the standard tapping machine over the entire relevant frequency range, both for the separating wall of EN 14366-1 and for that of EN 17823.

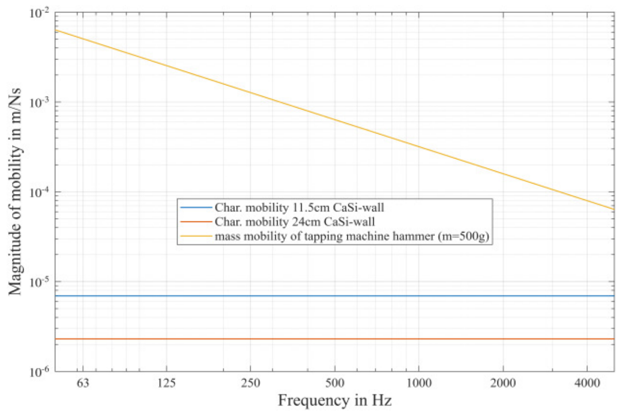

Figure 3. Comparison of the characteristic mobility of the separating wall in the building-like test facility and in the stair test facility with the mass mobility of one hammer of the standard tapping machine.

3. Simplification for force-source conditions

For the calibration source the corresponding relation holds without any simplification, because the injected power W_{cal} is determined from the real part of the cross spectrum of force F_{cal} and velocity v_{cal} at the contact point. The receiver mobility is therefore not an independent quantity here, but is defined by these two measured quantities. For the real part of the mobility, ISO 7626-1 [8] gives:

$$\mathrm{Re}\{Y_R\} = \frac{W_{cal}}{\tilde{F}^2_{cal}} \tag{7}$$

Rearranged for W_{cal} and expressed in levels:

$$L_{W,cal} = L_{F,cal} + 10 \cdot \log_{10}(\mathrm{Re}\{Y_R\}/Y_0) \tag{8}$$

For the standard tapping machine, Eq. (8) in the same form (cf. Eq. (4)) is only applicable under the assumption of a force-source condition, in which the contact force equals the blocked force. Under this condition the power of both the calibration source and the tapping machine can be calculated from the force of the respective source and the real part of the receiver mobility. Inserting Eqs. (2), (4) and (8) into Eq. (3) yields:

$$L'_n = L_{p,cal} - L_{F,cal} + L_{Fb,eq,stm} + 10\log_{10}\left(\frac{A}{A_0}\right) \tag{9}$$

Here $L_{p,cal}$ is the SPL measured in the receiving room when the element is excited by a calibration source of known force level $L_{F,cal}$. The receiver mobility $\mathrm{Re}\{Y_R\}$ cancels out completely: the normalised impact SPL therefore follows solely from the comparison of the force levels of the calibration source and of the tapping machine and from the measured sound pressure. It should be noted that the two force levels are different: that of the calibration source is the force actually acting at its contact point and is measured there, whereas that of the tapping machine is its equivalent blocked force. Only the latter relies on the force-source condition. Force and sound pressure are field quantities that can be measured directly in third-octave bands; the measurement of complex-valued quantities and the narrowband evaluation are no longer required.

3.1 Third-octave band averaging of the mobility

EN 17823 requires an evaluation in third-octave bands. By analogy with Eq. (7), the mobility in third-octave bands would have to be determined from the real part of the power in third-octave bands and the auto spectrum of the blocked force in third-octave bands:

$$\mathrm{Re}\{Y\}_{1/3oct,direct} = \frac{W_{1/3oct}}{\tilde{F}^2_{1/3oct}} \tag{10}$$

EN 15657, in contrast, defines the mobility in third-octave bands as the arithmetic mean of the M narrowband mobility values k within the third-octave band [7]:

$$\mathrm{Re}\{Y\}_{1/3oct,EN15657} = \frac{1}{M}\sum_{k}^{M} \mathrm{Re}\{Y_k\} \tag{11}$$

For a force spectrum that is constant over frequency, Eqs. (10) and (11) yield identical results. If individual frequencies within a third-octave band are excited more strongly than others, Eqs. (10) and (11) yield different results, see Fig. 4. Because of this inconsistent third-octave band averaging, the mobility does not cancel out completely in the power-based method and a systematic error remains. Complete cancellation of the mobility furthermore requires that power and mobility originate from exactly the same calibration measurement; otherwise the repeatability between separate measurements introduces additional errors. With the simplified method based on the force comparison this error does not occur, because no mobility has to be determined. The simplified method thus reduces both the measurement effort and the uncertainties.

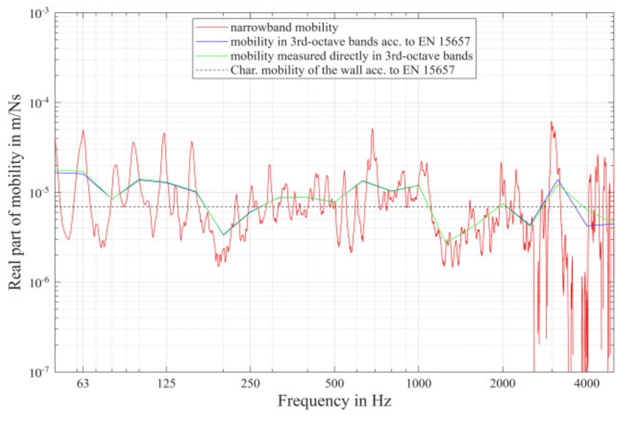

Figure 4. Real part of the mobility of the 11.5 cm wall in the building-like test facility – measured with narrowband resolution (red), in third-octave bands according to Eq. (11) (blue) and directly in third-octave bands according to Eq. (10) (green).

Where no force-source condition is present – as is often the case in lightweight construction – a determination of the transfer function directly in third-octave bands would be desirable as well, but it can currently only be realised by accepting additional uncertainties [9].

3.2 Comparison of the two methods

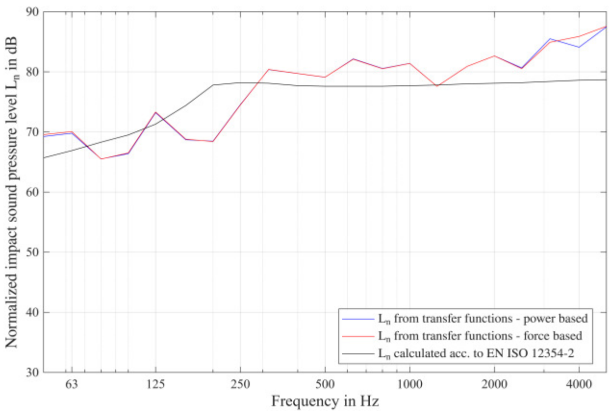

Figure 5. Normalised impact SPL of the 220 kg/m² calcium silicate wall in the building-like test facility: calculated according to EN ISO 12354-2 (black), determined from the power-based transfer function (blue) and from the force-based transfer function (red).

Fig. 5 compares the normalised impact SPLs determined with both methods. The black curve is the normalised impact SPL calculated according to EN ISO 12354-2 and serves as a reference. If both methods are evaluated consistently in narrow bands, they are mathematically equivalent – the blue and the red curve would coincide completely. The deviations between them arise exclusively from the inconsistent third-octave band averaging of the mobility discussed above (cf. Eqs. (10) and (11)); the force-based method is not affected. Their magnitude depends on the excitation spectrum: for the shaker driven with white noise used here, as well as for measurements with an impact hammer, the deviations remain small, whereas for a strongly non-uniform excitation spectrum they grow accordingly.

Both transfer functions in Fig. 5 were determined for a single excitation point. For the normalised impact SPL of the complete wall, the element would have to be excited at several positions and the results averaged energetically over the N positions, as is done with the standard tapping machine. For the comparison of the two methods shown here a single point is sufficient, since both methods are evaluated from the same excitation.

For measurements with the standard tapping machine the force spectrum shows a substantial drop at high frequencies [10], caused by the limited contact stiffness. The methodology used here assumes – as is common in standardisation, e.g. in EN ISO 12354-2 [11] – the frequency-independent force spectrum of an ideal Dirac impulse [12] and therefore overestimates the normalised impact SPL at high frequencies [4].

4. Consequences for standardisation

The simplification shown is not limited to EN 17823 – it concerns all standards that use transfer functions based on the power substitution principle, wherever a force-source condition is present. In each of them the mobility fails to cancel for the reason given above, and in each of them it can be avoided in the same way.

4.1 EN ISO 10848-1

EN ISO 10848-1 defines the power-based building transfer function D_{TF}, see Eq. (2). By analogy, a force-based (index: F) building transfer function $D_{TF,F}$ should be defined, see Eq. (12). Where a force-source condition is present, it should be used preferentially.

$$D_{TF,F} = L_{p,cal} - L_{F,cal} \tag{12}$$

4.2 EN 15657

EN 15657 defines a transfer function from the installed power to the velocity of the receiving element (power substitution method) for the characterisation of BSE. An analogous simplification to a force-to-velocity transfer function is possible. Eq. (C.1) of EN 15657 can thus be simplified to Eq. (13).

$$\tilde{F}^2_{b,source} = \langle \tilde{v}^2_{source} \rangle \cdot \frac{\tilde{F}^2_{cal}}{\langle \tilde{v}^2_{cal} \rangle} \tag{13}$$

Expressed in levels for N contact points, analogous to Eq. (C.2) of EN 15657, this leads to Eq. (14):

$$L_{Fb,source} = L_{v,source} + 10 \log_{10} \left(\frac{1}{N} \sum_{i}^{N} 10^{(L_{F,cal,i} - L_{v,cal,i})/10} \right) \tag{14}$$

4.3 EN 14366-1

EN 14366-1 uses the power substitution method to determine the installed power of waste water systems in heavyweight construction and subsequently converts it back to the blocked force using the receiver mobility [2]. A direct determination via a force comparison, see Eq. (14), would be simpler and more accurate.

For all standards mentioned, the simplified method requires only the measurement of a force and of one further field quantity – sound pressure or velocity – directly in third-octave bands. A proposal for the implementation of the simplified method in standardisation is given in Table 1. It lists, for each of the four standards, the quantity currently defined and the force-based quantity proposed to be added alongside it. In all cases the proposal is additive: the power-based formulation remains available where no force-source condition is present.

Table 1. Proposal for the implementation of the simplified method in standardisation where a force-source condition is present.

Standard	Current state	Proposal
EN ISO 10848-1	Defines $D_{TF} = L_{p,cal} - L_{W,cal}$	Add $D_{TF,F} = L_{p,cal} - L_{F,cal}$
EN 17823	L_n' from D_{TF}	L_n' from $D_{TF,F}$
EN 15657	Defines the power substitution method	Add a force substitution method
EN 14366-1	Blocked force of the source from the power substitution method	Blocked force of the source from the force substitution method

5. In-situ application

The simplified method is also suitable for in-situ measurements in a completed building. If a wall on which building service equipment is to be mounted is excited by a known calibration source, the force-based transfer function $D_{TF,F}$ can be determined directly from the comparison of the force level $L_{F,cal}$ and the SPL $L_{p,cal}$ measured in third-octave bands in the receiving room. Together with the known force spectrum of the standard tapping machine, the normalised impact SPL can be predicted from this.

By comparing the normalised impact SPL used for the prediction with the measured one, it can be estimated whether an increased SPL is caused primarily by the equipment itself (higher blocked force) or by the building (higher normalised impact SPL). Furthermore, the presented method allows an in-situ determination of the blocked force of BSE, which is advantageous in particular for extended sources such as lifts [13].

6. Conclusions

It has been shown that the determination of the normalised impact SPL from the power-based building transfer function according to EN ISO 10848-1 can be simplified wherever a force-source condition is present, which in heavyweight construction is usually the case. Under this condition the receiver mobility cancels out of the calculation. The normalised impact SPL then follows directly from the comparison of the force levels of the calibration source and of the standard tapping machine together with the sound pressure measured for the calibration source. For a narrowband evaluation both methods lead to the same result. For the evaluation in third-octave bands required by the standards, the inconsistent third-octave band averaging of the mobility introduces a systematic error in the power-based method, which the simplified method avoids because it does not require a mobility at all. At the same time the measurement effort is reduced considerably: complex-valued narrowband quantities are no longer needed. The simplification should be incorporated into EN 17823, EN ISO 10848-1, EN 15657 and EN 14366-1.

7. Acknowledgments

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References

[1] *Building Acoustics – Estimation of Acoustic Performance of Buildings from the Performance of Elements – Part 5: Sound Levels Due to the Service Equipment*, EN 12354-5:2023.

[2] *Laboratory Measurement of Airborne and Structure-borne Sound from Service Equipment – Part 1: Application Rules for Waste Water Installations*, EN 14366-1:2023.

[3] L. Däuble, J. Scheck, and B. Zeitler, "Acoustical characterization of fresh and waste water systems – Towards a unified approach," in *Proc. DAS-DAGA 2025*, (Copenhagen, Denmark), 2025.

[4] C. Knuth, S. Schoenwald, J. Scheck, and B. Zeitler, "Determination of the impact sound pressure level using transfer functions," in *Proc. Forum Acusticum 2023*, (Turin, Italy), 2023.

[5] *Acoustic Properties of Building Elements and of Buildings – Laboratory Measurement of the Impact Sound Insulation of Stairs and Stair Isolating Elements*, EN 17823:2024.

[6] *Acoustics – Laboratory and Field Measurement of Flanking Transmission for Airborne, Impact and Building Service Equipment Sound between Adjoining Rooms – Part 1: Frame Document*, EN ISO 10848-1:2017.

[7] *Acoustic Properties of Building Elements and of Buildings – Laboratory Measurement of Structure-borne Sound from Building Service Equipment for All Installation Conditions*, EN 15657:2017.

[8] *Mechanical Vibration and Shock – Experimental Determination of Mechanical Mobility – Part 1: Basic Terms and Definitions, and Transducer Specifications*, ISO 7626-1:2011.

[9] G. Boschatzke, F. Schöpfer, and S. Mecking, "Direkte Messung von Körperschallübertragungsfunktionen in Terzbändern," in *Proc. DAGA 2026* Dresden, Germany, 2026.

[10] V. Wittstock, H. Bietz, and M. Schmelzer, "The influence of the restitution coefficient and multiple impacts on the force exerted by ISO tapping machines," *Acta Acustica*, vol. 9, 2025.

[11] *Building Acoustics – Estimation of Acoustic Performance of Buildings from the Performance of Elements – Part 2: Impact Sound Insulation between Rooms*, EN ISO 12354-2:2017.

[12] L. Cremer and M. Heckl, *Körperschall: Physikalische Grundlagen und Anwendungen*. Berlin: Springer-Verlag, 1996.

[13] A. Blödt and C. Höller, "Bestimmung der Schallleistung von Aufzugschächten aus Massivholz mit Hilfe eines Körperschall-Ersatzquellenverfahrens," in *Proc. DAGA 2023* Hamburg, Germany, 2023.