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PREDICTING NOISE FROM BUILDING SERVICE EQUIPMENT – REVIEW OF THE CURRENT SITUATION AND FUTURE RESEARCH NEEDS

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Abstract

The calculation method to predict noise from building service equipment according to EN 12354-5 has seen significant improvements and gained acceptance in recent years. In some countries (e. g. Germany), it is also finding its way into national building regulations as a means to show compliance with requirements. Still, there is more research needed for the prediction of noise from building service equipment to reach the same level of acceptance and usage as the prediction of airborne and impact sound insulation. In this contribution, the current situation of prediction methods for noise from building services is reviewed, focusing on technical as well as normative aspects. An overview is provided on the relevant standards (e.g. EN 12354-5, EN 15657, EN ISO 10848) and their relationship. Based on this overview, the needs for future research are identified. These include research questions regarding the sources, the receivers, their coupling, as well as questions concerning the predicted quantities and their uncertainties. A companion contribution by Scheck et al. focuses on characterisation methods for noise sources from sanitary installations and the relevant standards (e. g. EN 14366-1, future EN 14366-2, EN ISO 3822).

Keywords: *building acoustics, prediction methods, building service equipment, EN 12354-5, EN 15657*

1. Introduction

Showing compliance with building regulations regarding noise from building service equipment (BSE) typically involves in-situ measurements according to EN ISO 10052:2020 or EN ISO 16032:2024. The prediction of noise levels from BSE has not been widely adopted in practice, even though the standard EN 12354-5 has existed since 2009. The first version of the standard was applicable to heavy, homogeneous constructions only. The latest version of EN 12354-5 has been expanded to apply to all construction types. The input data required for the prediction can be obtained using the measurement methods defined in EN 15657 or EN 14366-1. These standards, too, have seen significant developments in recent years [1]. This contribution aims to provide an overview of the current situation of prediction methods and the methods to determine the required input data for noise from BSE, and to highlight ongoing and future research needs in this area.

2. Summary of the prediction method

In this section, the prediction method according to EN 12354-5:2023 [2] is briefly summarised. Both airborne and structure-borne excitation must be considered. The apparent normalised sound pressure level due to BSE in the receiving room is the energetic sum of all transmission paths of airborne and structure-borne sound:

$$L'_{\mathrm{ne}} = 10 \lg \left(\sum_{k=1}^{N_{\mathrm{a}}} 10^{L'_{\mathrm{ne,a,k}}/10} + \sum_{m=1}^{N_{\mathrm{s}}} 10^{L'_{\mathrm{ne,s,m}}/10} \right) \quad (1)$$

Here, $L'_{\mathrm{ne,a}}$ is the apparent normalised sound pressure level for airborne excitation (index a), and $L'_{\mathrm{ne,s}}$ is the apparent normalised sound pressure level for structure-borne excitation (index s). N_{a} and N_{s} denote the number of sources for each excitation type. The index e signifies noise due to equipment. The calculation described in this section is performed in one-third octave bands; the calculation using single-number

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quantities is not allowed for noise from BSE. Since noise from BSE may be dominated by low-frequency content, the prediction should ideally be performed for frequency bands starting at 50 Hz.

2.1. Airborne sound

The calculation of the apparent normalised sound pressure level $L'_{\mathrm{ne,a}}$ due to airborne excitation is based on the sound power level of the source $L_{W\mathrm{a}}$. If the source is located in the receiving room (i. e. transmission in the same room), then $L_{\mathrm{ne,a}}$ is obtained as:

$$L_{\mathrm{ne,a}} = L_{W\mathrm{a}} - 4\,\mathrm{dB} \tag{2}$$

If the source is located in an adjacent room, then $L'_{\mathrm{ne,a}}$ is obtained as:

$$L'_{\mathrm{ne,a}} = L_{W\mathrm{a}} - 4\,\mathrm{dB} - R' - 10\lg\left(\frac{A_{\mathrm{S}}}{S}\right) \tag{3}$$

Here, R' is the apparent sound reduction index between source room and receiving room, A_{S} is the equivalent absorption area of the source room, and S is the area of the separating element between source and receiving room ($10\,\mathrm{m}^2$ for diagonal transmission).

Alternatively, the calculation of $L'_{\mathrm{ne,a}}$ can be performed using a global building transfer function:

$$L'_{\mathrm{ne,a}} = L'_{\mathrm{ne,a,0}} - L_{W0} + L_{W\mathrm{a}} \tag{4}$$

Here, $L'_{\mathrm{ne,a,0}}$ is the normalised sound pressure level in the receiving room when the source room is excited with an airborne sound source with a sound power level of $L_{W0} = 120\,\mathrm{dB}$, i. e. $W = 1\,\mathrm{W}$.

2.2. Structure-borne sound

The calculation of the apparent normalised sound pressure level $L'_{\mathrm{ne,s}}$ due to structure-borne excitation is more complicated, as the structure-borne sound power depends not only on the properties of the source, but also on the properties of the receiver. For this reason, EN 12354-5 makes a distinction between the *general case*, which is valid for all types of building elements, and a *special case*, in which the source mobility is significantly (i. e. at least 10 times) higher than the receiver mobility. This case is also called a *force source situation* and is usually the case for heavyweight and stiff buildings elements, such as concrete or masonry walls, or floating cement screeds.

In the general case, the apparent normalised sound pressure level $L'_{\mathrm{ne,s}}$ is obtained as:

$$L'_{\mathrm{ne,s}} = D_{\mathrm{TF,av,n}} + L_{W\mathrm{s}} \tag{5}$$

Here, $D_{\mathrm{TF,av,n}}$ is the normalised spatial average transmission function, and $L_{W\mathrm{s}}$ is the injected structure-borne sound power of the source.

The calculation of $L'_{\mathrm{ne,s}}$ can alternatively be performed using the equivalent notation as in Equation (4):

$$L'_{\mathrm{ne,s}} = L'_{\mathrm{ne,s,0}} - L_{W0} + L_{W\mathrm{s}} \tag{6}$$

Here, $L'_{\mathrm{ne,s,0}}$ is the normalised sound pressure level in the receiving room when the source room is excited with a structure-borne sound source with a sound power level of $L_{W0} = 120\,\mathrm{dB}$, i. e. $W = 1\,\mathrm{W}$.

The approach of using a sound pressure related to a given excitation is the same approach that has been used for decades for impact sound insulation with the standard tapping machine. Therefore, in the special case, in which the mobility of the source is much higher than the mobility of the receiver structure, the normalised sound pressure level $L'_{\mathrm{ne,s}}$ is obtained as:

$$L'_{\mathrm{ne,s}} = L'_{\mathrm{n}} - L_{F\mathrm{b,eq,stm}} + L_{F\mathrm{b,eq}} \tag{7}$$

Here, L'_{n} is the normalised impact sound pressure level, $L_{F\mathrm{b,eq,stm}}$ is the equivalent blocked force level of the standard tapping machine, and $L_{F\mathrm{b,eq}}$ is the equivalent blocked force level of the structure-borne sound source under investigation.

3. Determination of input parameters

For the prediction method described in the previous section to work, input data of the sources and the receivers are required. In this section, a brief overview is given on the methods to obtain such input data. As the prediction is performed in one-third octave bands, the input data also needs to be determined in one-third octave bands.

3.1. Airborne sound

The airborne sound power level $L_{W\mathrm{a}}$ is usually available for typical BSE, however often only in single-number values. It can be determined using the methods of the ISO 347x series or the ISO 9614 series. The parameters R', A_{S} and S are also needed for the calculation of the airborne and impact sound insulation according to EN ISO 12354-1 and -2, hence they are readily available in most cases.

3.2. Structure-borne sound

The structure-borne sound source quantities needed for the prediction can be obtained using the procedures described in EN 15657 [3].

For the general case, the injected structure-borne source power is required. It depends not only on the properties of the source, but also on the properties of the receiver, and can be obtained as:

$$L_{W\mathrm{s}} \approx 10\lg\left(\frac{\mathrm{Re}\{Y_{\mathrm{R,eq}}\}\cdot Y_0}{|Y_{\mathrm{S,eq}}|^2 + |Y_{\mathrm{R,eq}}|^2}\right) + L_{v\mathrm{f,eq}} - 60\,\mathrm{dB} \tag{8}$$

$$\approx 10\lg\left(\frac{\mathrm{Re}\{Y_{\mathrm{R,eq}}\}/Y_0}{1 + |Y_{\mathrm{R,eq}}|^2 / |Y_{\mathrm{S,eq}}|^2}\right) + L_{F\mathrm{b,eq}} \tag{9}$$

Here, Y_{S} and Y_{R} are the mobilities of source and receiver, respectively, and $Y_0 = 1\,\mathrm{m/(N\,s)}$ is the reference mobility. $L_{F\mathrm{b,eq}}$ is the blocked force level, i. e. the force exerted by the source on a completely rigid, inert receiver structure. $L_{v\mathrm{f,eq}}$ is the free velocity level, i. e. the velocity at the contact points when the source is freely suspended. The index eq indicates that the quantities are *single equivalent values*; they incorporate all source contact points (N) and all degrees of freedom (M) of source and receiver. The use of absolute values for the mobilities in Equations (8) and (9) is a simplification [4], as mobilities are typically complex-valued quantities. Also, the calculations require averaging of narrowband mobility spectra to obtain one-third octave band data. The value of 60 dB in Equation (8) originates in the reference values when calculating levels in dB according to EN 15657: $F_0 = 1 \times 10^{-6}\,\mathrm{N}$, $v_0 = 1 \times 10^{-9}\,\mathrm{m/s}$, and $W_0 = 1 \times 10^{-12}\,\mathrm{W}$.

The quantities $L_{F\mathrm{b,eq}}$ and $L_{v\mathrm{f,eq}}$ can be determined by indirect measurement on reception plates. This is achieved by operating the source on a low-mobility ($|Y_\mathrm{S}| \gg |Y_\mathrm{R}|$) or high-mobility ($|Y_\mathrm{S}| \ll |Y_\mathrm{R}|$) reception plate according to EN 15657. First, the injected structure-borne sound power is determined by measuring the mean plate velocity level L_v and using the plate mass m and the plate total loss factor η:

$$L_{W\mathrm{s}} = 10\lg\left(\frac{2\pi f \cdot m \cdot \eta}{f_0 \cdot m_0}\right) + L_v - 60\,\mathrm{dB} \tag{10}$$

Here, $f_0 = 1\,\mathrm{Hz}$ and $m_0 = 1\,\mathrm{kg}$. From measurements on the low-mobility reception plate, the equivalent blocked force level $L_{F\mathrm{b,eq}}$ is estimated by accounting for the equivalent real part of the receiver mobility at the contact points $\mathrm{Re}\{Y_\mathrm{R,low,eq}\}$:

$$L_{F\mathrm{b,eq}} \approx L_{W\mathrm{s,low}} - 10\lg\left(\frac{\mathrm{Re}\{Y_\mathrm{R,low,eq}\}}{Y_0}\right) \tag{11}$$

The equivalent free velocity level $L_{v\mathrm{f,eq}}$ can be determined from direct measurements (by freely suspending the source) or from indirect measurements on a high-mobility reception plate:

$$L_{v\mathrm{f,eq}} \approx L_{W\mathrm{s,high}} + 10\lg\left(\frac{|Y_\mathrm{R,high,eq}|^2}{\mathrm{Re}\{Y_\mathrm{R,high,eq}\} \cdot Y_0}\right) + 60\,\mathrm{dB} \tag{12}$$

When both low-mobility and high-mobility reception plates are used, the absolute value of the equivalent source mobility $Y_\mathrm{S,eq}$ can also be determined:

$$|Y_\mathrm{S,eq}|^2 \approx Y_0^2 \cdot 10^{(L_{v\mathrm{f,eq}} - L_{F\mathrm{b,eq}})/10} \cdot 10^{-6} \tag{13}$$

This procedure is called the *two-stage reception plate method*. EN 15657 also defines a power substitution method to obtain the injected source power $L_{W\mathrm{s}}$. This method is relevant for the in-situ characterisation of extended sources such as wastewater pipes.

Besides the injected source power level $L_{W\mathrm{s}}$, the transmission function $D_\mathrm{TF,av,n}$ is required for the prediction in the general case. The transmission function D_TF is defined in EN ISO 10848-1 as the level difference between the injected structure-borne sound power level L_W at position k and the resulting average sound pressure level L_av in the receiving room:

$$D_{\mathrm{TF},k} = L_{\mathrm{av},k} - L_{W,k} \tag{14}$$

Averaging over multiple excitation positions yields the average transmission function $D_\mathrm{TF,av}$, which can be normalised with respect to the absorption area of the receiving room to give $D_\mathrm{TF,av,n}$:

$$D_\mathrm{TF,av,n} = D_\mathrm{TF,av} + 10\lg\left(\frac{A}{A_0}\right) \tag{15}$$

In the special case, in which the source mobility is significantly higher than the receiver mobility, the same approach can be used as in the general case. In addition, a more practical approach exists that does not require knowledge of $D_\mathrm{TF,av,n}$. This approach uses the normalised impact sound pressure level L'_n, which is usually needed anyway for the calculation of the impact sound insulation. It can be measured in-situ according to EN ISO 16283-2:2020 (if the receiving structure is a floor) or according to EN 17823:2025 (if the receiving structure is a wall), or it can be calculated for both cases according to EN ISO 12354-2:2017. The equivalent blocked force level of the standard tapping machine $L_{F\mathrm{b,eq,stm}}$ is provided in EN 12354-5, and the equivalent blocked force level of the source under investigation $L_{F\mathrm{b,eq}}$ is determined using the methods described above.
For the determination of input parameters for sanitary installations, specific measurement methods based on the general methods in EN 15657 are available. EN 14366-1 [5] specifies measurement methods for wastewater installations. A new standard for freshwater installations (EN 14366-2) is currently in preparation. These methods are discussed in a companion paper by Scheck et al. [6].

4. Current and future research

In this section, current research activities and future research needs are described, with references to literature where possible. The pursuit of these research activities can help to increase acceptance and usage of the methods described in the previous section.

4.1. Regarding sources

4.1.1. Data for real sources

One of the main challenges for the practical application of the prediction method according to EN 12354-5 is the availability of source data for structure-borne excitation (e. g. the equivalent blocked force level). So far, data for structure-borne source quantities have mostly been obtained in research projects for individual sources. Data sheets for BSE do not usually include source data for structure-borne excitation at the moment. In comparison, airborne sound power levels of machinery are usually available, though in many cases only as single-number quantities. It is anticipated that the demand for structure-borne source data will increase with the introduction of the prediction methods in national building regulations. This in turn could incentivise manufacturers of BSE to include structure-borne sound source data in their data sheets.

4.1.2. Operating conditions

For the prediction methods to yield accurate results, the input source data must be representative of the situation in the finished building. Research by Kruse et al. [7] has shown that the source quantities of certain machinery (e. g. heat pumps) can change drastically based on operating conditions. This highlights the need to provide data for representative operating conditions. If in doubt, it seems prudent to use a worst-case scenario for the prediction, i. e. the operating condition with the highest equivalent blocked force level.

4.1.3. Transient source signals

The methods in EN 12354-5 and EN 15657 have been developed for sources that emit stationary sounds. Real machinery in buildings usually emits sound that is transient in character, e. g. due to variable operating cycles. This raises the question how transient source signals can be handled in the prediction method and measurement procedures. This is particularly relevant as regulatory requirements are sometimes given in terms of maximum sound pressure levels (such as $L_{\mathrm{AF,max}}$) instead of average sound pressure levels (such as L_{eq}). Reinhold [8] investigated the characterisation and prediction of time-varying signals from structure-borne sound sources. Recent research by Rieger et al. [9], [10] has built on these studies and has shown how the methods of EN 15657 and EN 12354-5 can be adapted for transient signals.

4.1.4. Distributed sources

The methods in EN 12354-5 and EN 15657 have mostly been studied using individual, compact sources, i. e. sources that are mounted on a floor or a wall at a particular location in a building. Examples include heat pumps, compact air handling units, or individual climate control units. Other types of BSE require adjustments to the methods or in-situ measurements. For example, pipes and ducts are distributed sources that cannot easily be characterised using the methods in EN 15657. Scheck et al. [11] have performed case studies with pipes with promising results. Very large BSE requires in-situ measurements. For example, Bailhache et al. [12] have characterised a motorised garage door using in-situ measurements. Schanda et al. [13] investigated the applicability of the EN 15657 methods to characterise roller shutters mounted in window openings. Schöpfer et al. [14] presented adaptions of the method to cope with sources that are not typically mounted on the surface of walls or floors. Similarly, elevators can be an important source of noise in multi-family dwellings or hotels. Blödt and Höller [15] investigated how the source power of elevators can be determined by reciprocal measurements. More research and more case studies are needed to investigate large and distributed noise sources in buildings.

4.2. Regarding receivers

4.2.1. Lightweight receiver constructions

For the prediction of the normalised sound pressure level $L'_{\mathrm{ne,s}}$ with sources installed on lightweight receiver constructions, Equation (5) must typically be used. This requires the knowledge of the injected structure-borne sound power $L_{W\mathrm{s}}$ and the normalised spatial average transmission function $D_{\mathrm{TF,av,n}}$. Since the injected power depends on the properties of source *and* receiver, it is difficult to obtain without making assumptions about the source-receiver coupling in the finished building. This increases the uncertainties associated with the prediction for lightweight receiver constructions. However, even in lightweight buildings, the special case can be applied when, for example, a heavy cement screed is the receiver construction.

4.2.2. Transmission functions

Schöpfer et al. [16] have accumulated a large database of transmission functions $D_{\mathrm{TF,av,n}}$ in timber and hybrid constructions. The goal is a catalogue of typical transmission functions that can be used for the prediction in wood-framed buildings. More data is needed to increase this database and to allow statistical evaluations and a reduction of the uncertainties of the transmission functions.

The transmission function describes the transmission from the injected structure-borne sound power to the average sound pressure level in the receiving room. To determine the structure-borne sound power, measurements and calculations in narrowband spectra with complex-valued quantities are necessary. This makes the measurement and calculation of transmission functions rather cumbersome. Simplifications to these measurements would be very beneficial. In [17], Boschatzke et al. present an approach to measure the quantities in one-third octave bands with standard sound level analysers.

In heavyweight (e. g. concrete or masonry) buildings, the determination of the transmission function is usually not necessary, because the prediction uses Equation (7) rather than Equation (5). However, there are other use cases for the transmission function, e. g. for the determination of the normalised impact sound pressure level of walls in EN 17823 [18]. Research by Däuble et al. [19] shows that instead of the power transmission function, i. e. the transmission from power to sound pressure, the force transmission function can be used, i. e. the transmission from force to sound pressure level, assuming a low-mobility receiver. It is planned to include this simplification in the relevant standards (ISO 10848, EN 15657, EN 14366).

4.2.3. Transmission via more than one junction

The calculation procedure of the EN 12354 series currently accounts for transmission across one junction only. In practice, transmission paths across more than one junction may assume importance in some cases. In those cases, measured transfer functions can be used (if available).

4.3. Regarding general aspects

4.3.1. Uncertainties and validation studies

Like all prediction methods, the prediction method according to EN 12354-5 with input quantities from EN 15657 inherently involves uncertainties. These may be due to measurement uncertainties in the determination of the equivalent blocked force, or the use of equivalent values, or the use of frequency-band averages, or the general uncertainty associated with the prediction procedure according to the EN 12354 series. For a prediction method to gain acceptance, validation studies and the quantification of uncertainties are an important development. In [20], Wittstock et al. employ an idealised structure-borne sound source and the standard tapping machine to evaluate the uncertainties of the reception plate method in an interlaboratory test. Another interlaboratory test is currently underway for wastewater installations. The objective is the determination of the uncertainties associated with the source quantities of wastewater pipes (EN 14366-1). In addition to the uncertainties associated with the source quantities, the prediction method also involves an inherent uncertainty. Some validation studies have been performed in the past [21], [22], [23], but more validation studies are necessary to increase acceptance of the methods and quantify the uncertainties associated with the prediction.

4.3.2. Single-number quantities

In Germany, the calculation of airborne and impact sound insulation is performed purely in single-number quantities, i. e. frequency-dependent data is not used. The frequency-dependent calculation of noise from BSE according to EN 12354-5 therefore adds a level of complexity. Still, the end goal of the prediction is a single-number quantity that can be compared to regulatory requirements. This single-number quantity can be calculated at the end of the prediction by energetically adding up all frequency bands of the normalised sound pressure level L'_{ne}.

For manufacturers of BSE, it would be beneficial to include a single-number quantity in their data sheets (e. g. for product comparisons). This, however, poses a challenge, as the final value of L'_{ne} depends on the source *and* the receiver properties, including the entire transmission through the building. Giving a single-number quantity for the source quantities only (blocked force, free velocity, source mobility) would be misleading. The value for L'_{ne} can only be determined once the source quantities *and* the propagation through the building have been properly accounted for. A single-number quantity for the comparison of products which is valid for all building situations is therefore not possible. However, EN 12354-5 provides two example situations that allow the calculation of single-number quantities: one for the general case and one for the specific case.

4.3.3. Psychoacoustics

Noise levels due to BSE are typically relatively low compared to other sources. The reason why such noise can be disturbing is often due to tonal characteristics (e. g. low-frequency humming), or transient signals (e. g. valves opening and closing), or unpleasant associations (e. g. toilet flushes from neighbouring units). For this reason, noise from BSE should consider psychoacoustic metrics in addition to sound pressure levels. In a current research project, Kruse et al. [24] are investigating the psychoacoustic properties of wastewater noise.

4.3.4. User-friendly tools

Implementing the calculation procedure according to EN 12354-5 based on source quantities from EN 15657 (e. g. in Excel or MATLAB) is relatively easy in practice, unless the calculation models of EN 12354-1 and EN 12354-2 are also used. However, access to all relevant data is required. This is currently a significant barrier for the adoption of the prediction methods in the market. One solution to this problem could be dedicated software tools such as IBP Prenoise from Fraunhofer Institute for Building Physics (`https://www.prenoise.app/`). The tool uses relevant data for wastewater installations from manufacturers and provides the necessary calculations to yield the normalised sound pressure level in the receiving room [25].

5. Summary

The calculation method according to EN 12354-5 offers a convenient way to predict noise from BSE, using input data obtained from EN 15657 or EN 14366-1. The methods are established by now and have been refined and improved in recent years. There are still some research questions which should be addressed to increase the acceptance and usage of the methods in practice. In addition, more case studies and validation studies are needed to answer questions concerning the predicted quantities and their uncertainties.

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