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PREDICTION MODEL FOR SOUND TRANSMISSION FROM MACHINERY IN BUILDINGS: FEASIBLE APPROACHES AND PROBLEMS TO BE SOLVED

E. Gerretsen

TNO TPD, P.O. Box 155, 2600 AD, Delft, Netherlands

Tel.: +31 15 2692461 / Fax: +31 15 2692111 / Email: gerretsen@tpd.tno.nl

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ABSTRACT
Prediction models for the airborne and impact sound transmission in buildings have recently been established (EN 12354-1&2:1999). However, these models do not cover technical installations and machinery as a source of sound in buildings. Yet these can cause unacceptable sound levels and it is therefore desirable to have design tools available to predict sound levels caused by machinery in advance or to design measures to reduce the sound level in existing situations. Future parts of the EN 12354-series should treat that subject, but the best approach on an engineering level is not self-evident and there are still a lot of questions to be solved. That is especially so concerning structure-borne sound transmission, which is the focus point of this paper.

1 - INTRODUCTION
The transmission of air-borne and structure-borne sound from a machine or installation will in principle be comparable to that already treated in the EN-12354 standards [1], but the situation is much more complicated than in case of a loudspeaker (EN 12354-1) or a tapping machine (EN 12354-2) as sound source. The sources to be considered consist in general of several partial sources, will be connected to the building structure at various points and in various ways, can be a much more complicated source than just a force source, could be a predominant low frequency source etc. etc. And even if the description as structure-borne source could be rather simple, there are hardly any source data available nor measurement methods established to collect such data. Hence, the first task in establishing standardized prediction models is to consider feasible approaches for such a model on an engineering level and establish what are the additional activities to assure that the necessary input data on machinery and equipment will become available in the future. In this paper different approaches will be presented, as a start for a discussion for the best practical approach.

2 - BASIC ASSUMPTIONS FOR SOURCE AND TRANSMISSION MODELS
In general the sound levels in rooms due to technical installations and equipment are caused by a mixture of air-borne and structure-borne sound transmission. Which of those is dominant depends on the type of installations as well as on the type of building construction. Furthermore, technical installations often consist of several noise sources and several connection points between the installation and the building structure. The excitation of the structure by a source of structure-borne sound depends on several degrees of freedom (forces, moments, translational and angular velocities), several possible contact points with the structure and various impedance ratios between sources and mounting structures. This makes a general prediction method rather complicated and some simplification is necessary to get a practical approach. It will be necessary to divide the system or installation in components that can be considered as independent sources of air-borne and structure-borne noise. Which part of an installation or which combination of connecting points can be considered as a source will depend on the source mechanisms and type of equipment, but to be practical a realistic physical component should be chosen. For the characterisation of the emission of structure-borne sound sources several approaches are feasible [4, 5]. The best choice is not yet clear. The sound transmission for each of these sources could, in line with

the other parts, best be described by linear sound power models. Airborne sound transmission through pipes and ducts is not considered in this paper. The airborne sound transmission is just presented as a reference, since the focus will be on structure-borne sound.

3 - FEASIBLE MODEL APPROACHES

3.1 - Level difference approach

3.1.1 Airborne transmission through building construction

The already well-established quantity to express the source strength is the air-borne sound power W, normally expressed as the air-borne sound power level L_W. This is measured in accordance with several standardized methods. The resulting sound pressure in the source room depends mainly on the absorption in that room A_{source}. Normally the transmission between rooms is expressed by the normalized sound pressure level difference D_n between the source and receiving room.

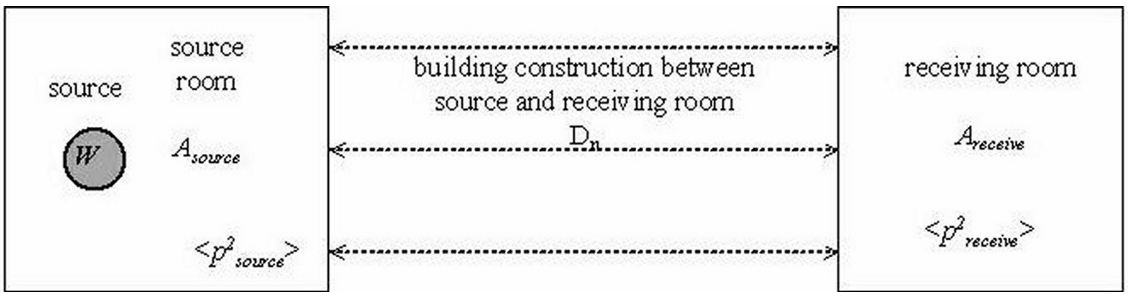

Figure 1: Airborne sound transmission from a source through a building.

The normalized sound pressure level $L_{p,n}$ in the receiving room follows from the sound power (L_W), the transmission to the resulting sound pressure in the source room (D_s) and the transmission through the building to the receiving room (D_n); see figure 1.

$$L_{p,n} = L_W - D_s - D_n$$
$$\text{with } D_n = L_{p,s} - L_{p,r} - 10\text{lg}A_r/A_{ref} \text{ and } D_s = 10\text{lg}\frac{p_s^2}{\rho c W} \quad (1)$$

The transmission in the source room D_s can, by assuming in first approximation a diffuse sound field in the source room, be estimated from the absorption in that room A_s, which can be estimated from material data, using prEN 12354-6 [3]. Of course, in complex situations more detailed sound field models should be used and often it will be necessary too, to take into account the small distances between source parts and the building structure.

The sound transmission through the building could be based on measurements (EN ISO 140-4) or can be estimated from knowledge of the building construction by considering all the transmission paths between the source and receiving room (EN 12354-1).

3.1.2 *Structure-borne transmission through building construction*

As yet there are hardly well-established quantities available to express the source strength for structure-borne sound, hence hardly any standardized measurement method is available [4], [6]. For installations, parts of installations and equipment as used in buildings, probably either the (equivalent) force (${F^2}_{eq}$) or the (equivalent) velocity (${v^2}_{eq}$) perpendicular to the mounting structure could be sufficient in most cases [2]. In both situations the building structure is excited by a (perpendicular) force, either directly or through the velocity excited connections characterised by a dynamic stiffness k. Using ISO reference values it follows that

$$\begin{array}{lc} \text{force source :} & L_F = L_{Feq} \\ \text{velocity source} & L_F = L_{veq} + L_k - 20\text{lg}f - 76 \end{array} \quad (2)$$

Emission measurement methods are established [6] for resiliently mounted sources (L_v). Methods for force sources, like the plate method, have been studied [7] but are not yet developed into standards.

The transmission between the excited structure and the source room could than be expressed − in analogy to air-borne transmission − by normalized force-pressure level difference $D_{Fp,n}$.

Thus the normalized sound pressure level in the receiving room follows from the applied force (L_F) and the transmission through the building to the receiving room ($D_{Fp,n}$); see figure 2.

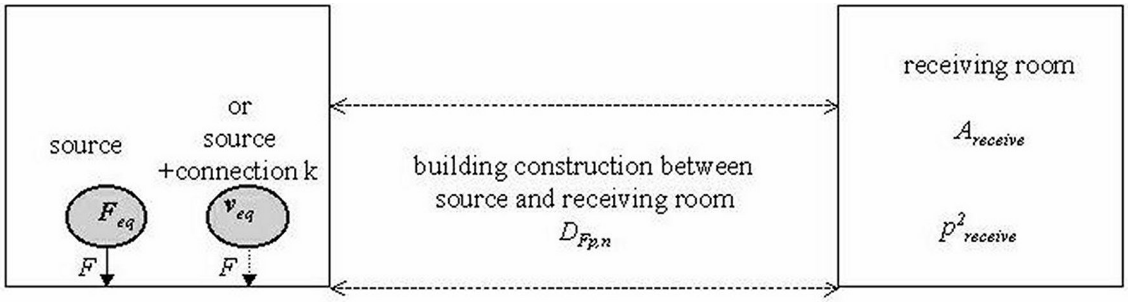

Figure 2: Structure-borne sound transmission from a source through a building.

$$L_{p,r,n} = L_F - D_{Fp,n} \text{ with } D_{Fp,n} = L_F - L_{p,r} - 10\text{lg}A_r/A_{ref} \tag{3}$$

The normalized force-pressure level difference $D_{Fp,n}$ can either be based on measurements (like in EN ISO 140-6) or can be estimated from knowledge of the building constructions (EN 12354-2). With the known force levels of the tapping machine the force-pressure level difference can be obtained directly from the normalized impact sound pressure level L_n according to those documents:

$$D_{Fp,n} = L_{F,ISO} - L_n \tag{4}$$

This is the approach that has been proposed and applied already earlier for air-borne and structure-borne sound sources [2].

3.2 - Separate transmission paths

On the basis of the same assumptions it could be advantageous to consider the different transmission paths from the source separately, expressing the transmission in the same type of quantities as in the parts 1 and 2 of EN 12354. For air-borne transmission this leads to:

$$p^2_{r,n} = \sum_{i,j} p^2_{ij,n} \text{ with } L_{p,ij,n} = L_W - D_{s,i} - R_{ij} - 10\text{lg}A_r/4 \tag{5}$$

The flanking sound insulation R_{ij} for such a path is defined in EN 12354-1 in relation to the area of the separating element. However, here it is more convenient to consider that area as a reference area and take it equal to the area of the excited structure S_i. The transmission $D_{s,i}$ is now the ratio of incident power to source power. In a diffuse field this will become $D_{s,i} = 10 \text{ lg } A_s/S_i$, but in this quantity all specifics of the sound field and source position could be included.

For structure-borne sources the transmission is than written in relation to the source spectrum of the standardized impact source (tapping machine) as:

$$p^2_{r,n} = \sum_{i,j} p^2_{ij,n} \text{ with } L_{p,ij,n} = (L_F - L_{F,ISO}) + L_{n,ij} \tag{6}$$

3.3 - Sound power transmission approach

Since equation (5) is actually describing the transmission by power ratio's, it could be advantages to make that more explicit for both air-borne and structure-borne sound transmission.

$$p^2_{ij,air,n} = \rho c W \frac{W_{inc,i}}{W} \frac{W_{rad,j}}{W_{inc,i}} \frac{p^2_{ij,air,n}}{\rho c W_{rad,j}} = \rho c W \frac{W_{inc,i}}{W} \frac{W_i}{W_{inc,i}} \frac{W_{rad,j}}{W_i} \frac{p^2_{ij,air,n}}{\rho c W_{rad,j}} \tag{7}$$

$$p^2_{ij,struc,n} = \rho c F^2 Re\left(Y_i\right) \frac{W_{rad,j}}{W_{inj,i}} \frac{p^2_{ij,struc,n}}{\rho c W_{rad,j}} = \rho c F^2 Re\left(Y_i\right) \frac{W_i}{W_{inj,i}} \frac{W_{rad,j}}{W_i} \frac{p^2_{ij,struc,n}}{\rho c W_{rad,j}} \tag{8}$$

As can be seen the transmission is equal in both cases starting from the sound power W_i in the structure i, as it results from the incident air-borne sound power W_{inc} or the injected structure-borne sound power W_{inj}. For the sound transmission in both cases a new quantity could be defined as the ratio $W_{rad,j} \,/\, W_i$, but is is probably more convenient to use the existing expressions for air-borne transmission (thus eq. 5). For structure-borne transmission the same quantity can than be used, adjusting it with the difference in power input (W_{inj}/W_{inc}). Eq. 6 would than be written as:

$$L_{p,ij,n} = L_F + 10\lg Re\left(Y_i\right) + 10\lg\frac{W_{inc,i}}{W_{inj,i}} - R_{ij} - 10\lg A_r/4 \tag{9}$$

The input power ratio for structure i can be estimated from its mobility at the source position and the sound reduction index. For a homogeneous structure this ratio turns out to depend only on frequency and the radiation efficiency.

3.4 - Structure-borne source sound power

So far the source has always been described as a force source (directly or from a resiliently mounted velocity source). Though this is probably acceptable for a lot of sources in heavier buildings, it certainly is not a general approach and it will lead to deviations in case of light mounting structures. In [5] the strength of sources is generally expressed as a characteristic structural sound power W_{sc} from which the injected power follows from a coupling term. This approach could be directly applied to eq. 8, replacing the first two terms (the injected power) by:

$$L_{Winj} = 10\lg\frac{W_{sc}}{W_o} + 10\lg\frac{W_{inj}}{W_{sc}} = L_{Wsc} + C \tag{10}$$

The characteristic structural sound power is just depending on source properties; the coupling term depends on source and structure properties and is typical for the combination. These quantities have the advantage of being general and theoretically well founded. Simple situations, as the ones considered before, are incorporated in the general case. But this approach has not found much practical application yet, so much study is still needed. For the time being the general approach could be applied to the simplified global approaches used now. In case of a perpendicular force source the results would be:

$$L_{Wsc} = L_F + 10\lg Re\left(Y_s\right) \text{ and } C = 10\lg\frac{Re\left(Y_i\right)}{Re\left(Y_s\right)} \tag{11}$$

In case the source mobility is indeed very high, as would be the case for a pure force source, this clearly leads to non-realistic values. For a logical connection between the 'old' and this new approach it could be useful to define a reference mobility in these cases in stead of using the, yet unknown but very high, real source mobility.

In case of a resiliently mounted velocity source, the characteristic structural power and coupling term would become:

$$L_{Wsc} = L_v + 10\lg\mathrm{Re}\left(Z_s\right) \text{ and } C = 10\lg\frac{k^2}{\omega^2}\frac{Re\left(Y_i\right)}{Re\left(Z_s\right)} \tag{12}$$

This indeed leads to the same power injection as does eq. 2. A pure velocity source would have an impedance tending to infinity, again a reason to define a reference impedance for this type of sources.

4 - DISCUSSION

The air-borne sound transmission for machinery and installations can be modelled in a quite comparable way to the model for air-borne sound insulation between rooms in EN 12354-1. Describing the source as a sound power source fits well to such a modelling, though various specific effects, like the vicinity of structures and non-Sabine sound fields, will have to be taken into account.

For the structure-borne sources the transmission through the structure could probably most practically be treated in the same way, starting from the sound power injected by the source. It is less logical to use here the same quantities as in EN 12354-2, since there the tapping machine as a source is included in the quantities used. Describing the structure-borne sound emission by sources is the most difficult part here. Assuming simplified source behaviour (force source, velocity source) makes the model approach rather practical, but narrows the field of application. Using the proposed characteristic structural sound power has the elegance of being general, but is not yet practically applicable. It would be worthwhile to study the possibility to incorporate the first approach in the second one, to be able to use the little experience available while further developing the more general approach.

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