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Towards a prediction of the sound transmission from lightweight stairs

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The sound transmission from lightweight stairs which are connected to separating walls often gives rise for complaints. One reason for this is that at present there is no prediction method available. Treating the stair as an active component in a similar manner like vibrating machines stairs can be characterised as structure-borne sound sources. The source data then can be used to predict the sound transmission in buildings using parts of EN 12354. Following this approach investigations on a timber stair have been carried out in a staircase test facility. Based on a full characterisation by contact free velocity and mobility and in-situ measurement using an indirect method, more practical methods like the reception plate method and a characterisation based on a reference power calibration are investigated. The source data obtained was used to predict the sound transmission in buildings.

1 Introduction

This paper reports on investigations aimed to provide a laboratory characterisation of lightweight stairs as structure-borne sound sources, in order to then predict the sound transmission in buildings using parts of EN 12354. The characterisation sought was to be on a power basis. Three methods were considered and compared. The first method is based on source activity and mobility and requires complex valued data [1]. However, significant data reduction is possible if unimportant components of excitation can be neglected. This was established by a reciprocal measurement method. The second method seeks to exploit the simplicity of the reception plate method, which has been successfully used previously for isolated plates in laboratories [2]. For practical reasons, a real wall is proposed as a reception plate. However, the obtained power is an underestimate of the source power. This is demonstrated experimentally using a shaker source of known input power. It also is confirmed by reference to Statistical Energy Analysis (SEA) that the underestimate is a result of power-sharing between the walls and floors connected to the reception wall. The third method circumvents this problem by calibrating the selected reception wall with a source of known power, again a shaker. The source considered for test was a lightweight timber stair with the string board rigidly point connected to a single-leaf wall (24 cm CaSi with density 2000 kg/m^3). The wall is connected to 2 similar side walls and 2 concrete floors and is contained in a test facility for stairs (Fig. 1).

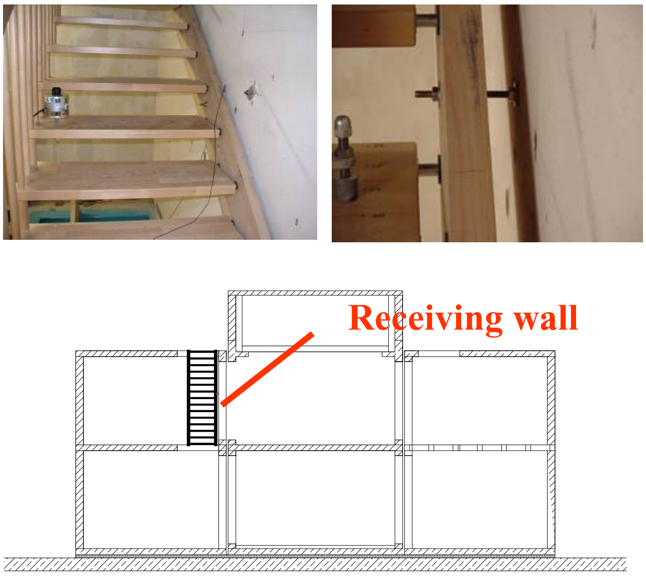


Fig.1 Investigated stair system (top) and test facility for stairs (bottom)

2 Source activity and mobility

Stairs firstly constitute passive structures that become active due to excitation by a walking person or a tapping machine. If the stair system and the excitation are treated as one system, then source characterisations developed for vibrating machines can be used. This is straightforward since the vibration behaviour of stairs is complicated and hardly predictable [3]. The source activity can be expressed as the free velocity or blocked force. The transmitted structure-borne sound power to a receiving structure then is a function of source activity and mobility and of receiver mobility [4]. For a full description of the transmission, three quantities are required for each contact and for up to six components of excitation at each contact [5-7]. An independent source characterisation is possible (the source descriptor), using the free velocity and source mobility [8]. Then when combined with the receiver mobility, in the form of the coupling function, the installed power is obtained (Fig. 2).

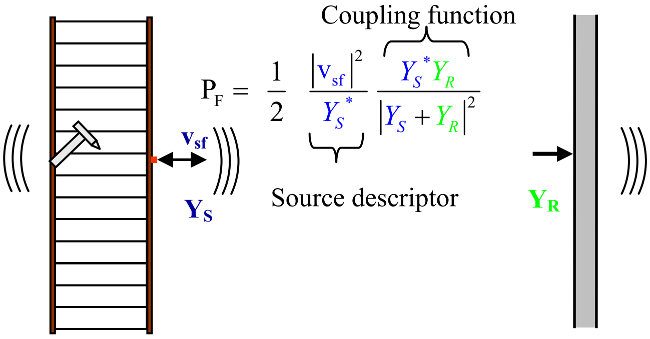
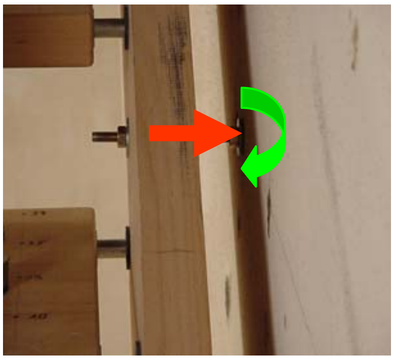

$$P_F = \frac{1}{2}\underbrace{\frac{|v_{sf}|^2}{Y_S^*}}_{\text{Source descriptor}}\overbrace{\frac{Y_S^* Y_R}{|Y_S+Y_R|^2}}^{\text{Coupling function}}$$

Fig.2 Stair as active component – source descriptor concept

The source activity of the stair strongly depends on the location of the excitation. This effect can be considered e.g. by means of averaging the free velocities to be measured over all steps.

2.1 Data reduction

The characterisation by free velocity and mobility becomes complicated or even intractable when several contacts and degrees of freedom have to be considered. There is a need to establish a hierarchy of the component power transmission (forces and moments) and thence, by elimination of the least influential components, simplify calculation. The power through several components of excitation was investigated in the installed condition using a reciprocal measurement method as described in [3, 9, 10]. The force perpendicular to the wall and the two moments around the axes in plane of the wall were considered (Fig. 3).



$$P_F = \frac{1}{2}\mathrm{Re}\left\{F \cdot v^*\right\}$$

$$P_M = \frac{1}{2}\mathrm{Re}\left\{M \cdot w^*\right\}$$

Fig. 3 Excitation of the wall by forces and moments

The stair was excited by a shaker attached to a central step and driven with random noise (Fig. 1). The reciprocally measured component powers are shown in Fig. 4.

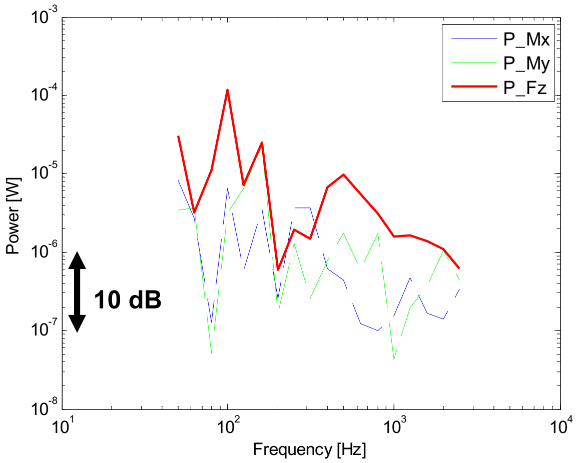


Fig. 4 Component power from stair excited by a shaker on central step

The force perpendicular to the wall is the predominant component in the case considered. This finding allows a significant simplification regarding the prediction of the sound transmission since only the translational component perpendicular to the wall has to be taken into account. A general statement about the role of forces and moments for all types of stairs cannot be deduced from this case study.

According to this result the free velocity (again with the shaker as external source) and mobility were measured with the stair disconnected from the wall as shown in Fig. 5.

Fig.5 Set-up for free velocity and mobility measurement

Fig. 6 shows the contact mobility of the stair to be significantly higher than the contact mobility of the wall. Mobility matching only occurs in the very low frequency range near the fundamental wall mode at 33 Hz. In general the stair constitutes a high-mobility source and thus the blocked force alternatively can be used to characterise the stair system. It can be assumed that this finding holds true for other lightweight stair systems (e.g. steel-wood constructions) since the variations in mass are not significant and also the variation of wall mobilities tends to be small due to requirements on the sound insulation of separating walls. The blocked force can be used as input for the prediction of the sound transmission in buildings according to 12354-2.

In Fig. 7 the power, predicted from free velocity and source and receiver mobility, and by reciprocal measurement, are compared. The agreement is within +/- 3 dB in the relevant frequency range up to 1 kHz. Thus, the free velocity and mobility method is generally applicable for stair systems as building elements.

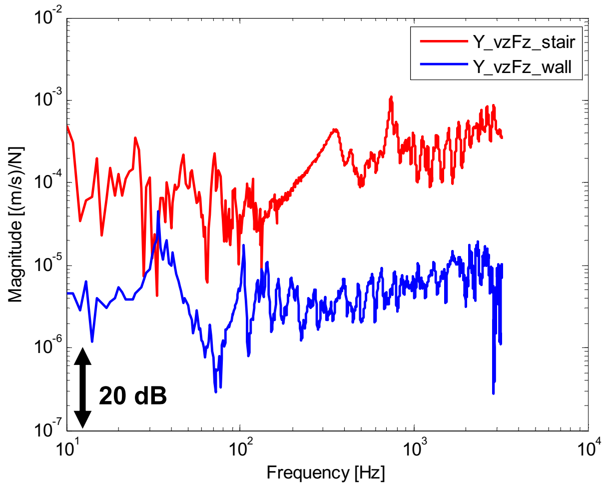


Fig.6 Contact mobility of stair and wall

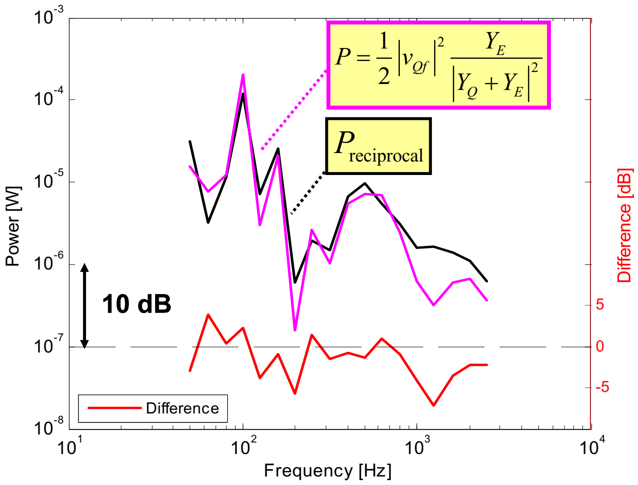


Fig.7 Power predicted from free velocity and mobility and from reciprocal measurement.

3 Reception plate method

The apparent advantage of the reception plate method, when compared to the free velocity and mobility method is the easy application and handling of the data. In [2, 10] it is demonstrated experimentally that the reception plate power equals the cross-spectral power from a connected shaker for free plates but not for walls or floors with the edges bonded into surrounding walls and floors like in real buildings. For the latter case, a consistent underestimate of the installed power was observed in previous investigations. This problem is addressed using a simplified SEA model.

3.1 Simplified SEA model

A Statistical Energy Analysis (SEA) representation of the reception plate method is given in Fig. 8.

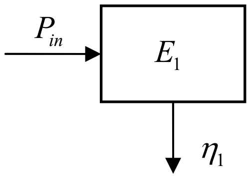


Fig.8 SEA model of a single freely suspended plate

The source power into the isolated plate equals the bending wave energy loss on the plate,

$$P_{in} = \omega E_1 \eta_1 \tag{1}$$

For an isolated plate, the total loss factor is equal to the internal loss factor η_1. The bending wave energy conserved in the plate equals the product of plate mass and spatial average velocity squared over the plate,

$$E_1 = m\bar{\tilde{v}}^2 \tag{2}$$

However, if we attach the source to a wall or floor in a building, then the excited plate is connected to other plates (i.e. walls and floors). Consider the simplest case where the reception wall is connected to a second plate at one edge (Fig. 9).

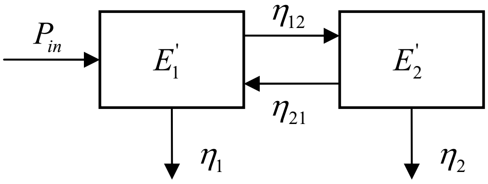


Fig.9 SEA model of two connected plates

The power balance equation for plate 1 is now a function of internal and coupling loss factors,

$$P_{in} = \omega E_1'(\eta_1 + \eta_{12}) - \omega E_2' \eta_{21} \tag{3}$$

The power balance equation for plate 2 is given by,

$$\omega E_2'(\eta_2 + \eta_{21}) = \omega E_1' \eta_{12} \tag{4}$$

Substitution of equation 4 into equation 3 yields,

$$P_{in} = \omega E_1'(\eta_1 + \eta_{12}) - \frac{\omega E_1' \eta_{21} \eta_{12}}{\eta_2 + \eta_{21}} \tag{5}$$

With the assumption that the shaker power into the single free plate 1 is the same as into plate 1 when connected to plate 2, then from (1) and (5) the discrepancy of the plate 1 energy can be expressed as (6).

$$\frac{E_1}{E_1'} = 1 + \frac{\eta_{12}}{\eta_1} - \frac{\eta_{21}\eta_{12}}{\eta_1(\eta_2 + \eta_{21})} \tag{6}$$

Prior to measuring the spatial average square velocity, the loss factor of plate 1 will be obtained as a total loss factor $\eta_{tot} = (\eta_1 + \eta_{12})$ rather than the internal loss factor η_1 of equation (1). Assume the two plates are similar such that $\eta_1 = \eta_2; \eta_{21} = \eta_{12}$. Estimates for the coupling and internal loss factors in buildings can be found in [11], where

$$\eta_{tot} = \frac{1}{\sqrt{f}} + 0.015 \tag{7}$$

Using these values of loss factor, the ratio E_1 / E_1' is about 2 at low frequencies and about 1.5 at high frequencies and thus for two connected plates, the reception plate method would underestimate the exact power by about 3 dB and 2 dB, respectively.

In buildings, walls and floors are usually connected to many more plates (side walls, etc). With the gross assumption of *N* similar plates with the connected plates only interacting with the directly excited plate 1, all connected plates have the same energy and the energy discrepancy is obtained as,

$$\frac{E_1}{E_1'} = 1 + N\frac{\eta_{12}}{\eta_1} - N\frac{\eta_{21}\eta_{12}}{\eta_1(\eta_2 + \eta_{21})} \tag{8}$$

For 4 connected plates the reception plate method underestimates the exact power by about 6 dB at low frequencies and by 4 dB at high frequencies.

3.2 Experimental investigation

A shaker with a force transducer, for direct power measurement, was attached to the wall and driven with random noise. The spatial average velocity was recorded using a Polytec laser scanning vibrometer on a scanning grid with in total 1100 points distributed over the whole wall surface (Fig. 10).

Fig.10 Shaker attached to the wall (left) and laser scanning grid with 1100 points (right)

In Fig. 11 the directly measured power is compared to the value obtained by the reception plate method. Also shown is the value obtained by reciprocal measurements.

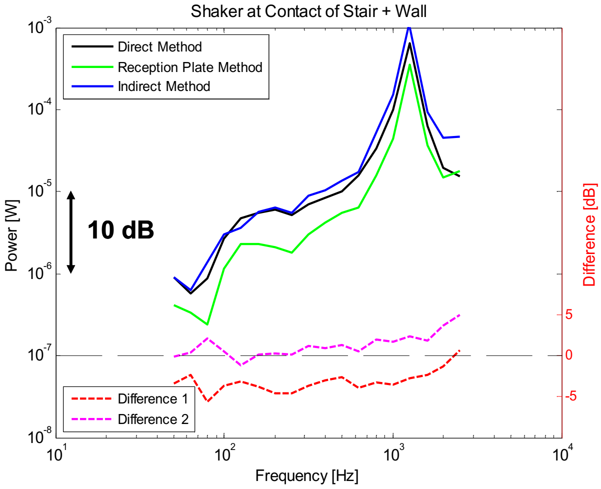


Fig.11 In-situ power from a shaker source attached to wall

The reciprocally measured power overestimates the exact power but is within 2 dB at frequencies up to 1600 Hz. The reception plate power underestimates the exact power. The discrepancy is about 5 dB at low frequencies and reduces with frequency, as predicted from the simplified SEA model. So far, loss factors according to [11] were used for the prediction of the discrepancies. It is well known that the coupling loss factor in (7) tends to overestimate the edge losses in modern buildings [12]. Therefore a more detailed investigation involving measured coupling loss factors is in progress.

4 Power substitution method

The reception plate method as applied so far yields a systematic underestimate of the real source power for coupled plates. The discrepancy depends on the boundary conditions – but in a linear system, it is independent from the source. Therefore a power calibration [13] can be used to circumvent this problem.

Fig. 12 and Fig. 13 show the power from the vibrating stair excited by a shaker and the tapping machine obtained by the reception plate method, using the power calibration function and by the reciprocal method. Again a significant underestimation of the stair power by the reception plate method is observed. Using the power calibration function an acceptable agreement is obtained. The method is thus found very useful for the purpose of characterising sources where the use of coupled reception plates only is possible or practical.

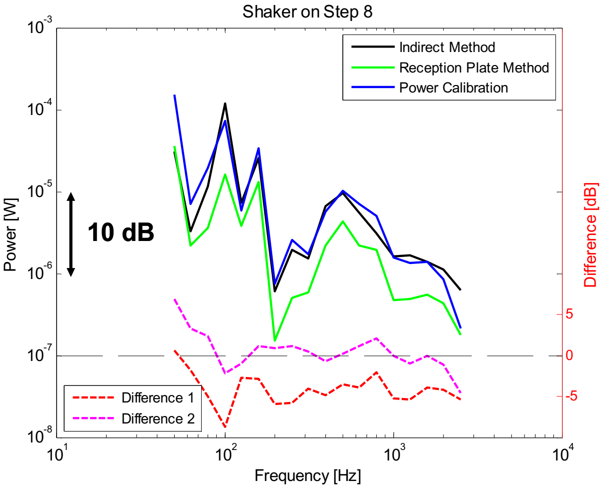


Fig.12 In-situ power from the stair excited by a shaker driven with random noise

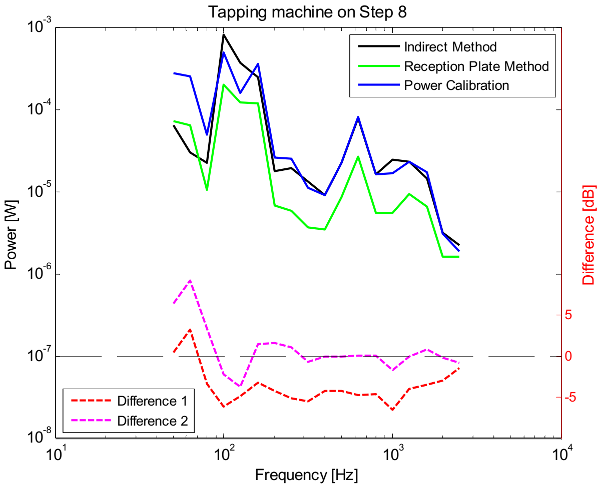


Fig.13 In-situ power from the stair excited by the tapping machine

5 Conclusion

A mobility method, a reception plate method and a power substitution method have been considered to characterise structure-borne sound sources, with a timber stair system as a case study. Stairs are treated as active elements with respect to an arbitrary external excitation e.g. by the tapping machine or a walking person. A precise characterisation is obtained from the free velocity and mobility. For the investigated timber stair, the characterisation can be reduced to one component which is the force perpendicular to the receiving structure. Furthermore the stair constitutes a high-mobility source when attached to typical separating walls in solid buildings. Data acquisition for the (future) prediction of the sound transmission from lightweight stairs according to EN 12354 is thus significantly simplified. The blocked force can be used to characterise the stair system at least when solid building situations are considered.

The reception plate method gives a systematic underestimate for reception plates coupled to other plates, such as is found in buildings. This was confirmed experimentally and by a simplified SEA model.

A power substitution method was successfully applied as a simple characterisation of structure-borne sound sources where the use of coupled reception plates, such as walls and floors, only is possible or practical.

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