Some practical aspects of the prediction of structure-borne sound caused by house-hold equipment

Eddy Gerretsen

TNO Science and Industry, Stieljesweg 1, 2628CK Delft, Netherlands
eddy.gerretsen@tno.nl

Sound levels in rooms due to service equipment in the building can be an important reason for disturbance and more so in light weight building structures. Though the recently published draft standard prEN 12354-5 gives a framework for the prediction of the structure-borne sound as caused by this type of sources, there is still a lot to be studied and developed. That is certainly the case for light weight building structures. Some possibilities to simplify the indicated models have been studied and experimental data has been gathered for house hold equipment, taking a washing machine as an example, applied both in a 'heavy' and in a 'light weight' building. Various possibilities to apply substitution methods to characterise such a source as structure-borne sound source have been tried and compared.

1 Introduction

Sound levels due to service equipment in buildings is one of the causes for annoyance and yet the possibilities to design a building and an installation to avoid such annoyance are still limited. This is partly due to the complexity of the combination of airborne and structure-borne sound generation and transmission involved. Especially for structure-borne sound practical methods to characterize sources and estimate sound propagation have been missing. Fortunately, this item got more intention over the recent years, resulting in first proposals for prediction methods [1] and source characterisation methods [2]. But various aspects are still to be studied especially the possibilities to simplify the approaches and the applicability to light weight buildings structures. Some of these aspects for structure-borne sound generation and transmission will be addressed in this paper.

2 Transmission model

2.1 Simple approach

The simplest approach is a one-dimensional modelling of a source as a perpendicular force F_s at one contact point with the structure, the source being generally characterised with source mobility Y_s. With a low source mobility compared to the mobility Y_r of the receiving structure it is a pure force source. The power injected by this source into the structure is than given by:

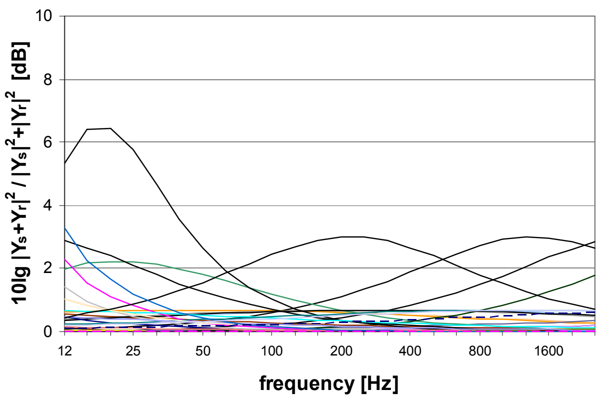
$$W_{inj} = \frac{F_{s,eff}^2}{\left|1 + Y_r / Y_s\right|^2} \mathrm{Re}(Y_r) = W_{s,c} / C_c \qquad (1)$$

This injected power is considered as the starting point for the estimation of sound transmission through the building in the model described in prEN 12354-5 [1]. There, this equation is split into a source part, the characteristic structure-borne sound power $W_{s,c}$ and a connecting term C_c: as indicated in Eq. (1) with:

$$C_c = \frac{\left|Y_s + Y_r\right|^2}{\left|Y_s\right| \mathrm{Re}(Y_r)} \qquad (2)$$

Applying these equations we would actually need a complete model for the source and receiver mobility, including real and imaginary part. Though the receiver will often be a plate, which mobility is essentially real, the source can in principle be anything. Assuming various basic types of mobilities for the source, like mass, spring, plate or beam, and using plate or beam-like mobilities for the receiving structure it was checked if Eq. (2). could be simplified by neglecting the complex mobility. The receiving structure is modeled as a plate or a beam varying from 200 mm concrete to 20 mm wood; the source is modeled as spring-, mass, beam or plate of steel varying from 5 mm tot 100 mm as typical dimensions. The results are given in Fig. 1 showing that indeed Eq. (2) could be written as in Eq. (3) without a large error, especially since the error gives a power estimation that is always on the safe side. For plate-like receiving structures the error is always less than 3 dB, for beam-like structures it could be somewhat larger.

$$\left|Y_s + Y_r\right|^2 \approx \left|Y_s\right|^2 + \left|Y_r\right|^2 \qquad (3)$$



.Fig.1 Error in simplification by Eq. (3) for various mobility types for source and receiving structure.

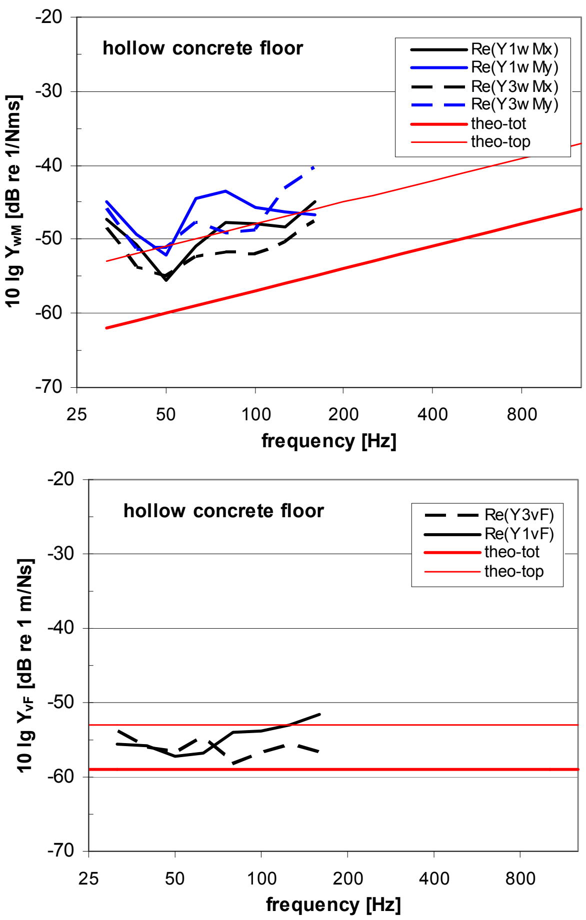
The exact model for the source mobility thus seems less important which could be especially relevant if we would use this simple source representation as an equivalent to a real source with for instance several connecting points.

2.2 Moment mobility

It is likely that in some cases a moment at a connecting point or between such points could be of importance for the injected power. In that case also moment mobilities are relevant. Normally these are more difficult to measure, but for the real part a rather easy method is available to estimate it. This method is based on the assumption that for excitation of the resonant vibration of a structure, hence excitation at some distance from the considered point, the power in all vibration modes will be equal and thus the ratio of the real parts of the mobilities is equal to the ratio of the related velocities [3]. Thus, knowing the mobility for translational vibrations and force, Y_{vF}, the mobility for moment and angular velocity, Y_{wM}, can be estimated by measuring the ratio of angular and translational velocity at that point. The angular velocity *w* can be easily estimated from the difference in velocity between two adjacent points (analogue difference or determined from auto- and cross-correlation between the two signals)

$$\mathrm{Re}(Y_{wM}) = \frac{w^2}{v^2}\mathrm{Re}(Y_{vF}) \qquad (4)$$

This approach was applied in a two-storey dwelling with light weight wooden based structures and a heavy hollow concrete ground floor. So tests could be performed in a similar way on that ground floor and on the light weight floating floor on a wooden basic floor. The tapping machine was used to excite the floors at some distance from a point in the central floor area where the velocities were measured, using a distance of 7,5 cm between the two accelerometers for the angular velocity.



.Fig.2 Real part of moment and force mobility of hollow concrete floor.

In Fig. 2 and 3. the results are given, both for the force mobility at two positions on the floor (distance about 60 cm) as for the moment mobility in two perpendicular directions. The results are compared with theoretical values for an infinite plate. For the hollow concrete floor it is clear that both mobilities are larger than that of an equally heavy (390 kg/m^2) homogeneous floor; the values compare better when considering only the top part of the floor. There is a small difference between the moment mobilities in the direction parallel and perpendicular tot the hollow tubes in the floor. For the light weight floating floor (36 kg/m^2) the theoretical values compare reasonably well with the measured values; though at higher frequencies the values for position 3 starts to deviate. For the moment mobility at low frequencies there is a clear difference between the two directions; whether is caused by the beams in the base floor is not clear. These measurement results clearly show the potential of this rather easy measurement method to determine various point mobilities.

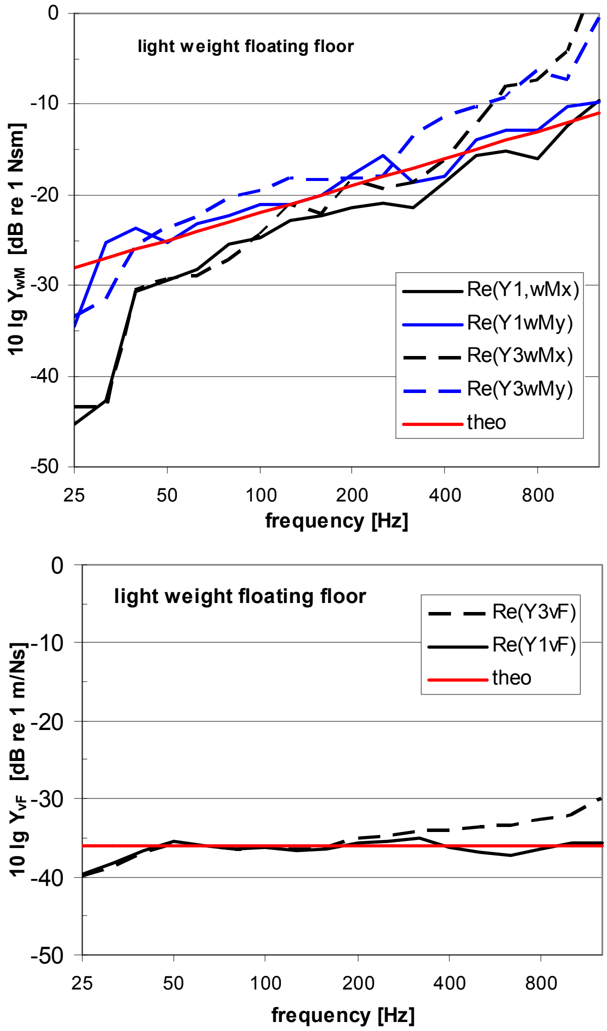


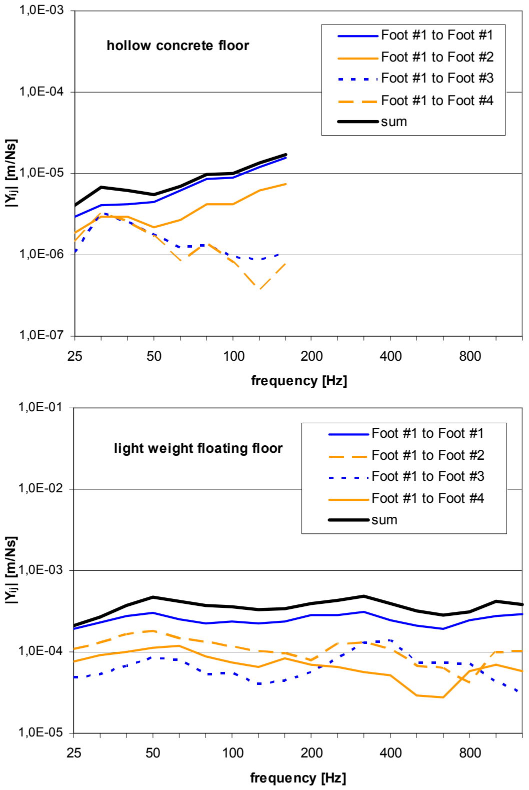
Fig.3 Real part of moment and force mobility of light weight floating floor.

2.3 Several connecting points

The simple representation could be used for a real source with several contact points if we use effective values for the source and receiver mobilities [4, 5]. This approach still needs some assumptions on the source, especially the relation between the forces at the different contact point. In [6] it was argued and demonstrated that for washing machine the easier assumption of random forces is just as plausible as that of coherent forces. Following [5] the effective mobilities could than be written as:

$$\mathrm{Re}(Y_r^{eff}) \approx \mathrm{Re}(Y_r) \text{ and } |Y_r^{eff}|^2 \approx \sum |Yri,j|^2 \qquad (5)$$

In Fig. 4 results of the transfer mobility and sum are given on the two floors for one of the contact positions of a washing machine with four contact points at about 50x50 cm. The effective value from Eq. (5) is in both cases slightly larger than the point mobility at one contact point. Results for the other contact points show similar results.



.Fig.4 Magnitude of point and transfer mobility between four machine contact points on light weight and concrete floor; square-root of sum as in Eq. 5 also indicated.

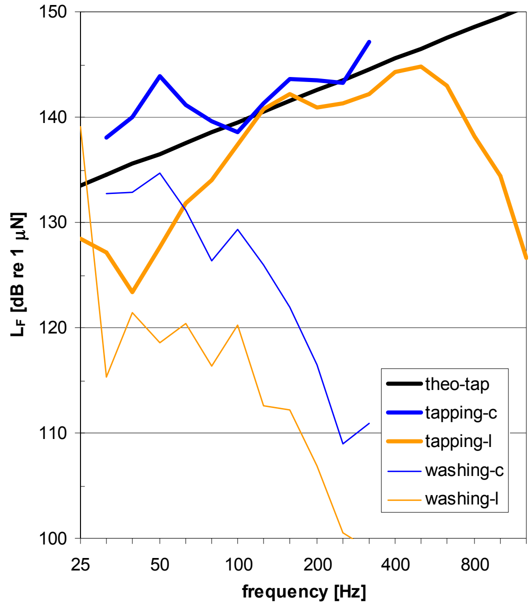


Fig.4 Force level as determined by the reception plate method with tapping machine and washing machine on two floor types: **c**oncrete and **l**ight weight; theoretical value for tapping machine for comparison.

3 Source characterization methods

3.1 Plate methods

The equivalent force as applied at the contact points, a starting point for the source sound power, can be derived from the so-called reception plate method:

$$F_{eq}^2 = \overline{v^2} \frac{2{,}2 M 2\pi}{T_s \operatorname{Re}(Y)} \qquad (6)$$

In this case this method is applied for the two floors in the dwelling describe in 2.2 using the tapping machine and a washing machine as source. The average velocity v^2 is measured on 6 position on the floor, the point mobility is measured (see 2.1) and the structural reverberation time is measured; the total mass M is estimated from the effective floor area and the mass of the floor. This method is applied to the tapping machine and a household washing machine as source on both the hollow concrete and the light weight floating floor. The results in Fig. 5 show for the tapping machine deviations from the expected at low frequencies for both floors; the deviations at higher frequencies on the light floor are as expected since the mobility mismatch is insufficient on this floor to consider the tapping machine as a pure force source and also the contact stiffness of the two floor is different. It is not clear whether the deviations at low frequencies are caused by peculiarities of the floors or measurement insufficiencies. As for the washing machine there is a clear difference between the results on the two floors. It is to be seen if this can be explained by the ratio of source and floor mobilities.

3.2 Substitution method

Assuming the tapping machine as a known force source, which is no longer the case at higher frequencies on the light weight floating floor as shown in Fig. 4, the substitution method could be applied to determine the force level of the washing machine:

$$F_{eq,wash}^2 = F_{tapping}^2 \frac{\overline{v_{wash}^2}}{\overline{v_{tap}^2}} \qquad (7)$$

This has also been applied using the hammer blows used for the mobility measurements as substitution source.

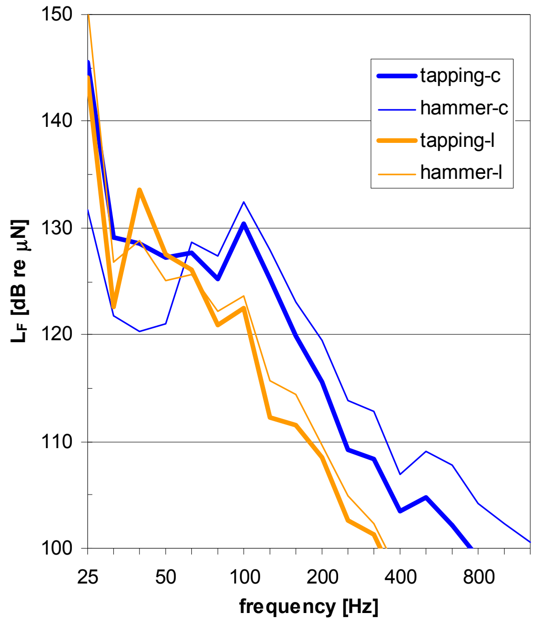


Fig.5 Force level of the washing machine as determined by the substitution method using the tapping machine or calibrated hammer blows on two floor types: **c**oncrete and **l**ight weight.

The results for the two floors are presented in Fig. 5 and compare reasonably well for the two different substitution sources, certainly considering that for the hammers the force is measured and for the tapping machine theoretically estimated. Again there is a clear difference between the force levels for the washing machine on the two floor type. From about 80 Hz on the difference is comparable with that in Fig 4, at lower frequencies both results are quite different.

3.3 Transfer mobility method

A comparable method as in 3.2 uses the transfer mobilities Y_{ij} between points i in the source area and reception points j at some distance on the floor. Assuming random excitation at the four feet the mobility from the four feet to a reception point should be added, as in Eq. (5). The final force level would be the average result over the different reception points, in this case 6 positions.

$$F_{eq}^2 = \frac{1}{N}\sum_{j=1}^{N} F_{eq,j}^2 \quad \text{with } F_{eq,j}^2 = v_j^2 \,/\, \sum_i \left|Y_{ij}\right|^2 \qquad (8)$$

For the same situations as before the results for this method are given in Fig. 6.

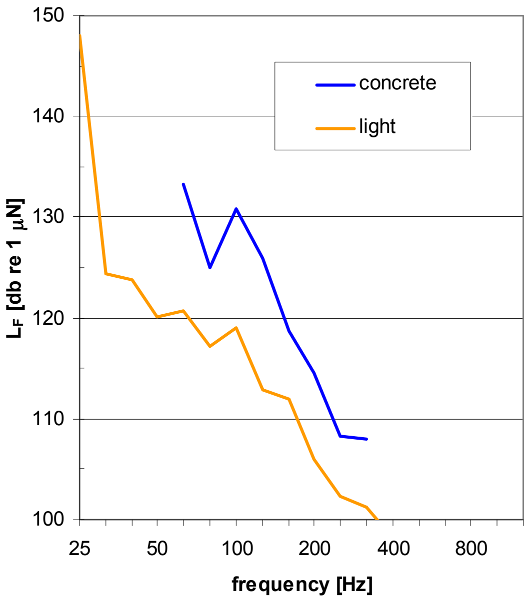


Fig.6 Force level of the washing machine as determined by transfer mobility method on two floor types: concrete and light weight.

The difference between the two floor types is again comparable to the differences with the other methods, but for the lowest frequencies.

3.4 Comparison

The results of the various methods in the two situations are compared in Fig. 7 for the tapping machine as source and in Fig. 8 for the washing machine as source. For the tapping machine the results are about equal, within 5 dB, between 80 Hz and 500 Hz and compare quite well with the theoretical value. At lower frequencies there is a spread in results both between methods as between floors. At higher frequencies the deviations between floors will be partly due the fact that for the lighter floor the tapping machine is no longer a force source, though also the different contact stiffness will be of importance here.

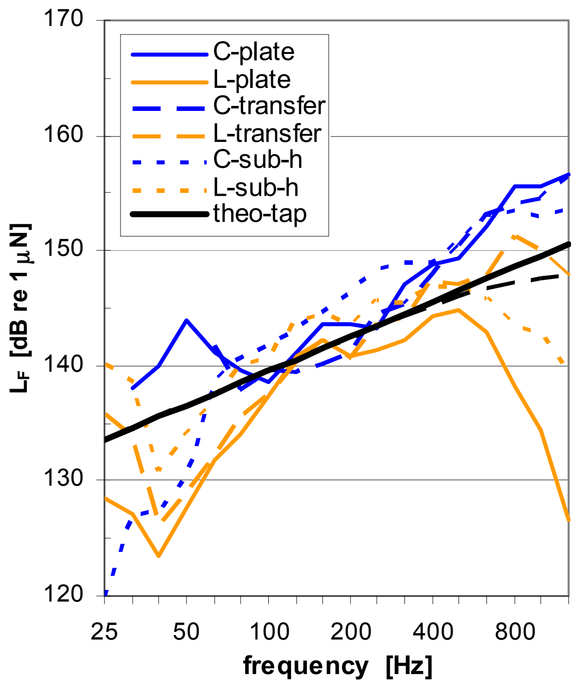


Fig.7 Force level of the tapping machine as determined with different methods on the two different floors; comparison with theoretical value.

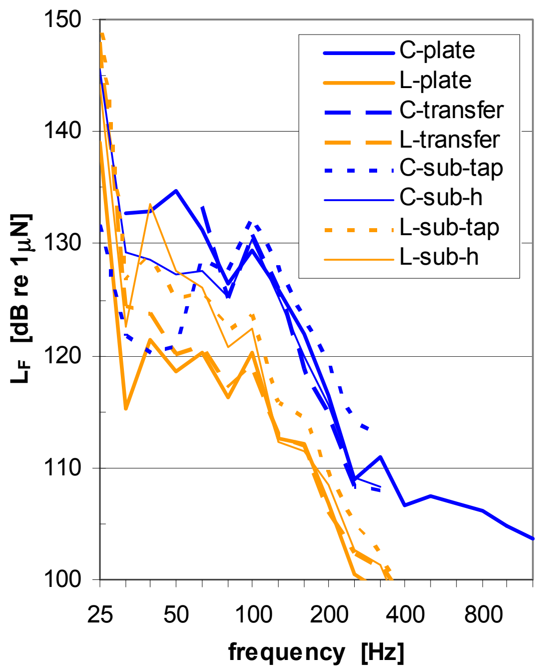


Fig.8 Force level of the washing machine as determined with different methods on the two different floors.

For the washing machine the results of the various methods coincide quite well from about 80 Hz onwards; at lower frequencies there is a larger deviation. The difference between the force levels on the two floor types indicate clearly that the washing machine is no force source (low source mobility), at least not for the light weight floating floor.

The results for the measurements on the two floors (**c** and **l**) can be used to estimate the magnitude of the source mobility $|Y_s|$ of the washing machine. If we use the approximation of Eq. (3) the magnitude of the source mobility follows from:

$$|Y_s|^2 = \frac{F_c^2|Y_c|^2 - F_l^2|Y_l|^2}{F_l^2 - F_c^2} \qquad (9)$$

This has been applied to the different measurement methods with results as presented in Fig. 8. In [6] also directly measured values for the source impedance of a washing machine have been presented. That impedance showed the behavior of a damped mass. If we apply this 'model' here we get the 'theoretical' line using a mass of 6 kg and a real part of the impedance of 10 000 N/ms (damping), which reflects the trend of the measurement results reasonably well.

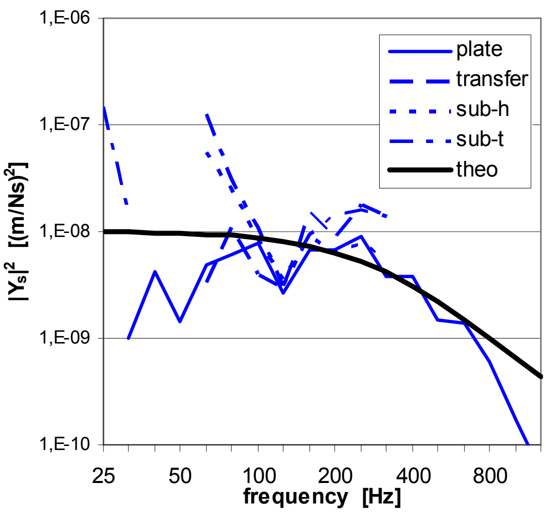


Fig.8 Magnitude of source mobility of the washing machine as determined from different measurement methods on the concrete and the light floor; theoretical value for a damped mass.

The same has also been applied to the tapping machine which should have the known source impedance of a mass of 0,5 kg. Though the measurement results show a trend of a mass-behavior for the midfrequency range, the corresponding mass value is up to a factor 3 larger.

Knowledge of the equivalent force level of the washing machine and the magnitude of the effective source mobility allows us to express the measurement results in a more general way as the characteristic structure-borne sound power by:

$$W_{s,c} = F_{eq}^2|Y_s| \qquad (10)$$

In combination with Eq. (1) this can be used for the prediction of resulting sound levels in adjoining rooms [1].

4 Conclusion

Some simplifications have been indicated to be able to treat structure-borne sound sources on an engineering accuracy level. Also various rather practical measurement methods have been tried and compared to determine the source strength of such sources, using the tapping machine and a washing machine as sound source. The results show the potentials of these methods, though there remain questions to be studied to improve the accuracy of results.

Applying the 'two-load' method an estimate of the source mobility of the washing machine has been determined; the results correspond globally with some earlier directly measured results. Source strength and source mobility allow to present the results as the characteristic structure-borne sound power level, a more general quantity as used in prediction model of prEN 12354-5.

References

[1] prEN 12354-5, *Buildings Acoustics – Estimation of acoustic performance of buildings from the performance of building elements- Part 5: Sound levels due to service equipment*, 2008

[2] prEN 15657-1, *Building Acoustics — Laboratory measurement of airborne and structure-borne sound from service equipment – Part 1: Simplified cases where the equipment mobilities are much higher than the receiver mobilities*, 2008.

[3] Verheij, J.W., *Simple experimental method for estimating frequency bandwidth averages of real parts of point admittances for six degrees of freedom*, Internoise Amsterdam, 1981

[4] Petersson, B. and J. Plunt "On effective mobilities in the predictin of structure-brone sound transmission between a source structure and a receiving structure", *Journal of Sound & Vibr* **82** (1982), 517-540

[5] Cookson, R.D. and N. Qi,.*A reception plate method of measurement of the free velocity source mobility of machines in buildings*, ICSV13 Vienna, 2006

[6] Gerretsen, E., *Structure-borne sound of equipment in buildings - characterisation and application of the source strength for washing machines as example*, ICA Roma, 2001