ACOUSTICS 2012

Prediction of structure-borne noise generated by a water evacuation duct in heavyweight and lightweight frame constructions

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This work aims at comparing structure-borne noise due to building service equipment, installed in heavyweight or lightweight buildings. The case of waste water pipes rigidly fixed to a separating wall is considered, and the resulting structure-borne noise in the adjacent room is predicted. The structure-borne sound power injected into the supporting structure is calculated using a source and receiver mobility approach. Characterization measurements are carried out to yield appropriate input data (source free velocity and source and receiver mobilities). Due to the large distance between the duct two fixing points, the duct is considered as two separate uncorrelated vibration sources. The spatial average velocity of the heavy concrete wall is then estimated from the injected power using the well known power balance equation, while an empirical relationship between power injected and wall velocity is established for the wood-framed wall. Radiated noise in the adjacent room is finally computed using an estimated radiation efficiency of the walls. Comparisons between heavy and lightweight walls are made in terms of injected structural power, wall velocity field and sound pressure level radiated.

1 Introduction

Building service equipment noise has recently been the subject of investigations aiming at its prediction. In particular, these investigations have led to two European standards:

- EN 12354-5 [1], which defines the calculation of noise generated by service equipment in buildings

- EN 15657-1 [3], which specifies a laboratory method for measuring the equipment structure-borne sound power. This power can be used as input data in the model described in EN 12354-5.

However, these methods are limited to the case of service equipment installed in heavyweight buildings. Concerning prediction in lightweight constructions, work is underway within the group CEN/TC126/WG2; concerning source characterization, a draft standard prEN 15657-2 is currently being prepared by standardization group CEN/TC126/WG7.

In the present study, this characterization method is applied, considering a simple and realistic case of equipment: waste water pipes. The structure-borne sound power injected into the supporting structure is characterized with the goal of estimating the noise radiated by the supporting wall and comparing results for heavyweight and lightweight structures.

2 Structure-borne noise prediction method

In the general case, the structure borne noise generated in a room by service equipment installed in a neighboring room is transmitted through the supporting wall (direct path) and through junctions to adjacent elements (flanking paths).

In heavyweight buildings, structure borne noise can be predicted using the method described in European standard EN 12354-5. Based on Statistical Energy Analysis (SEA), this method requires knowledge of the source installed power, which can be estimated according to EN 15657-1. Unfortunately, in lightweight constructions, inhomogeneous vibration fields are encountered, due to the presence of stiffeners and highly damped components and the prediction method has to be adapted. Also the mobility conditions between equipment and supporting structures lead to different expressions for the installed power.

In the present work, a simplified configuration, limited to the direct transmission path only is considered, as represented in Figure 1.

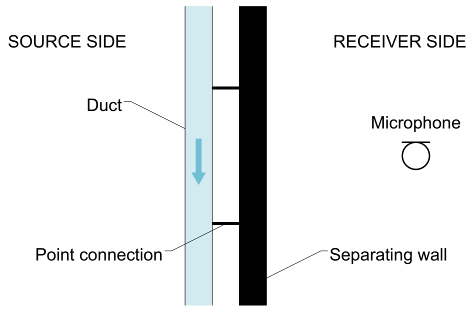

Figure 1: Simplified configuration considered

2.1 Installed power calculation

The equipment installed power, i.e. the structural power injected into the supporting structure, can be calculated by a mobility approach, first described by Petersson and Plunt [6], and more recently adapted by Gibbs, Qi and Moorhouse [7], and Mayr and Gibbs [8, 9]. In this approach, the vibration source and the receiving structure element are considered as rigidly fixed to each other through point connections. As a simplification, only the component of excitation normal to the receiver plane is considered. Indeed, previous researches [10] have shown that the influence of moments could sometimes be neglected. In the case of single-point connected source and receiver, the installed power $W_{s,inst}$ can be estimated as in Eq. (1) from source and receiver mobilities, and from the source free velocity at the contact point.

$$W_{s,inst} = \frac{1}{2} \frac{\mathrm{Re}\left\{\overline{Y_R}\right\}}{\left|\overline{Y_R} + \overline{Y_S}\right|^2} \left|\overline{v_{sf}}\right|^2 \tag{1}$$

In Eq. (1), $\overline{Y_S}$ and $\overline{Y_R}$ are respectively the source and receiver complex mobilities at the contact point and $\overline{v_{sf}}$ is the source free velocity at the contact point (vibration velocity when the source is disconnected from the receiver).

In the case of multiple-point connected systems, single equivalent mobility values can be defined, in which vibration transfer between the contact points is accounted for [11].

2.2 Direct transmission through heavy masonry structure

Heavy masonry walls and floors are homogeneous and have low internal loss factor and low input mobility. Only resonant transmission occurs and the structural power injected by the equipment into the supporting element generates a diffuse vibration field. The spatially averaged mean square velocity is assumed to be directly proportional to the installed power, according to Eq. (2), where f is the frequency, η is the total loss factor, m is the surface mass of the element and $\langle v^2 \rangle$ is the energetic space average of the vibration velocity.

$$W_{s,inst} = 2\pi f \eta m \langle v^2 \rangle \tag{2}$$

The vibrating wall or floor radiates sound in the adjacent room and the corresponding acoustic power can be calculated using Eq. (3), in which ρ_0 is the density of air, c the speed of sound, σ_s the radiation efficiency of the radiating element under structural excitation and S its surface area.

$$W_{ray} = \rho_0 c \sigma_s S \langle v^2 \rangle \tag{3}$$

In the present work, a simplified method is used to estimate the radiation efficiency from the critical frequency of the heavy wall.

2.3 Direct transmission through lightweight structure

Unlike heavy masonry building elements, lightweight elements are inhomogeneous structures. The presence of stiffeners – studs in walls, joists in floors – and the relatively high damping of the components (e.g. wood, gypsum) are responsible for a non-diffuse vibration field with important spatial variations when the element is under structural excitation. Consequently, Eq. (2) is no longer valid and an empirical approach has been used to estimate the relationship between the installed power and the spatial average vibration velocity of the wood-framed walls and floors. A relationship (Eq. (4)) can be established, in which the frequency dependent factor K is a characteristic of the building element under study.

$$W_{S,inst} = K \langle v^2 \rangle \tag{4}$$

Once the supporting structure vibration velocity is estimated using this empirical power balance equation, the radiated acoustic power can be calculated according to Eq. (3), where the radiation efficiency is determined experimentally from laboratory tests.

2.4 Equipment noise level calculation

The acoustic pressure in the receiving room is linked to the radiated sound power as described by Eq. (5).

$$W_{ray} = \frac{p^2}{4\rho_0 c} A \tag{5}$$

In Eq. (5), p is the acoustic pressure and A is the equivalent sound absorption area of the receiving room.

Assuming an equivalent absorption area of 10 m², the normalized sound pressure level can be calculated according to Eq. (6), where, in the case of lightweight construction, the term $10\log(2\pi f \eta m)$ is replaced by measured values of factor K defined in Eq. (4).

$$\begin{aligned} L_{sn} &= L_{Ws,inst} + 10\log(\sigma_s) + 10\log(S) \\ &\quad - 10\log(2\pi f \eta m) + 22 \end{aligned} \tag{6}$$

In Eq. (6), $L_{Ws,inst}$ is the installed power level in dB re. 10^{-12} W.

3 Description of the systems under study

The prediction method described above is applied to the simple case of a waste water duct rigidly fixed to a separating wall through two contact points, as installed in the CSTB laboratory (see Figure 2). The separating wall is either an heavy wall made of 100 mm thick concrete blocks or a lightweight wall (see Figure 3) made of two panels (10 mm thick OSB and 12.5 mm thick gypsum board) screwed on a wood frame (wood studs with 600 mm spacing). The distance between the two contact points is 1.25 m. The water flow rate in the duct (1, 2 or 4 litter/s) is controlled by the operator.

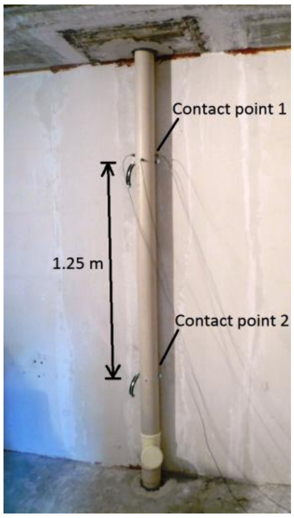

Figure 2: View of the waste water pipe installed on a heavyweight separating wall

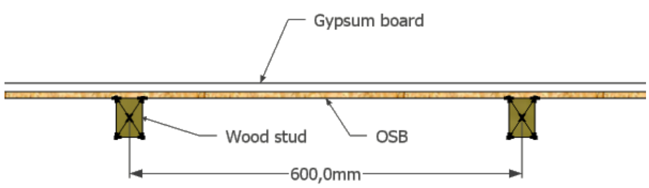

Figure 3: Lightweight separating wall under study (top view)

3.1 Source characterization tests

Input mobilities at the contact points are measured using electrodynamic excitation, the duct being disconnected from the supporting wall and without any water flowing through the duct. The experimental method is similar to ISO 7626-2 [4]. For practical reasons, separate sensors are used to measure force and velocity. The force transducer and accelerometer are installed on the duct approximately 20 mm from each other, opposite from the wall. Measurements are performed in third octave frequency bands in the range 50-5000 Hz. The experimental setup is shown in Figure 4 and Figure 5 shows the source mobility results.

The source free velocities at the contact points are also characterized with the duct disconnected from the wall, according to a direct method similar to ISO 9611 [5]. The water flow rate is set to 1 l/s, 2 l/s and 4 l/s. Measurement results are shown in Figure 6.

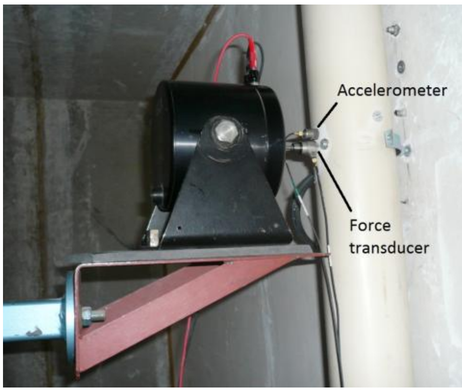

Figure 4: Experimental setup used for source point mobility measurements

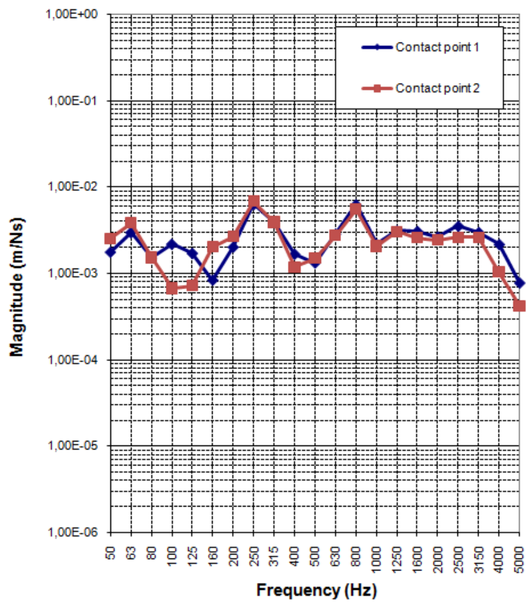

Figure 5: Measured source point mobilities

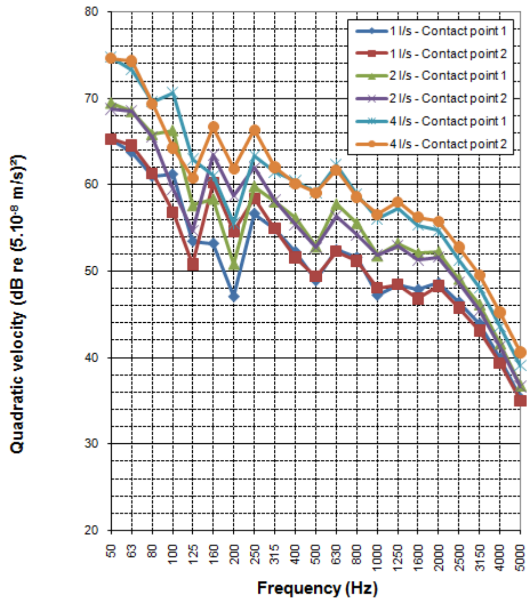

Figure 6: Measured source free velocities

3.2 Receiver characterization tests

The input mobility of the supporting walls is also measured at the locations where the duct is supposed to be attached. Only the case of contact points located between two studs is considered.

Measurement results are shown in Figure 7. It can be seen that input mobility values for the lightweight wall are of the same order as the source mobilities. In contrast, the heavy receiver mobility is 100 times lower.

Remark: some points are missing on the curves related to the lightweight receiver, due to high measurement uncertainties.

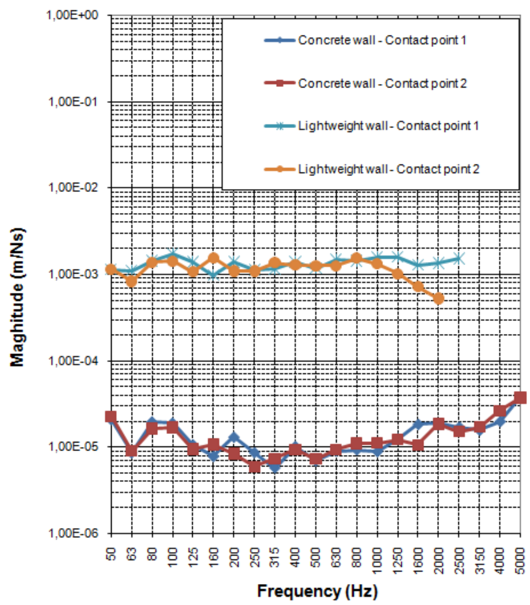

Figure 7: Measured receivers point mobilities

Additional tests have been performed to investigate the response of the lightweight receiver under structural excitation. An electrodynamic excitation was applied at several locations and for each location, both the injected structural power and the spatially averaged wall velocity were measured in order to empirically estimate the frequency dependent factor K defined in Eq. (4); a value of K, averaged over all excitation locations was used in estimating the wall velocity from the source power injected.

4 Predicted results

Based on the characterization measurements described above, the installed power, the supporting wall spatially averaged velocity and the structure borne noise radiated (direct path only) were then estimated for both the heavy and lightweight walls and compared.

4.1 Installed structural power

The installed power due to various water flow rates in the duct was estimated using the mobility approach. Since the connections are separated by a large distance, the duct is considered as two uncorrelated point vibration sources.

Figure 8 presents the installed power calculation results for a water flow rate of 2 l/s, which is representative of an in situ toilet flushing.

It can be noticed that the installed power is approximately 15 dB higher in the case of the lightweight structure.

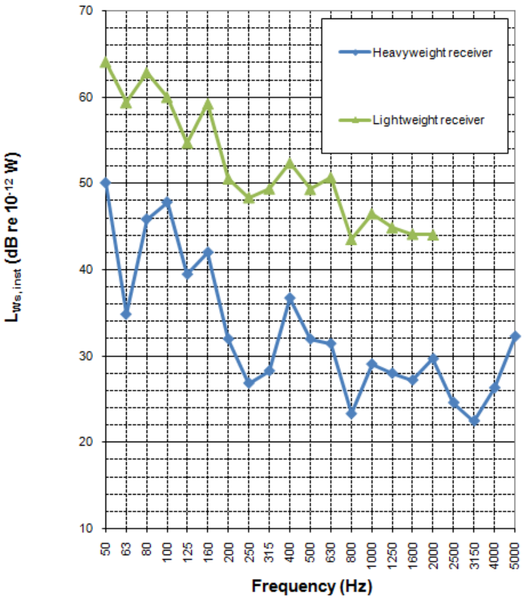

Figure 8: Predicted installed power - 2 l/s

4.2 Wall velocity

The spatially averaged vibration velocity of the supporting wall is calculated according to Eq. (2) or (4), depending on the nature of the receiver. Prediction results are presented in Figure 9.

It can be seen that the difference between the heavyweight and lightweight receiver responses is around 10 dB in the low frequency range and decreases with increasing frequency.

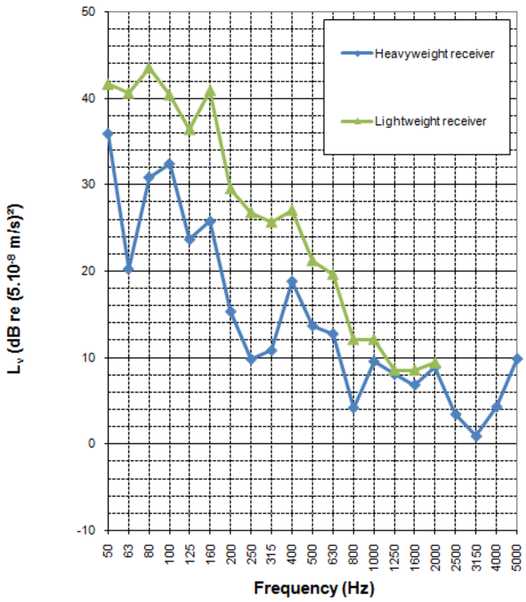

Figure 9: Predicted velocity level - 2 l/s

4.3 Radiated noise

The amount of noise radiated by the separating wall in the adjacent room is estimated according to Eq. (6). Input data concerning the radiation efficiency of the walls are presented in Figure 10.

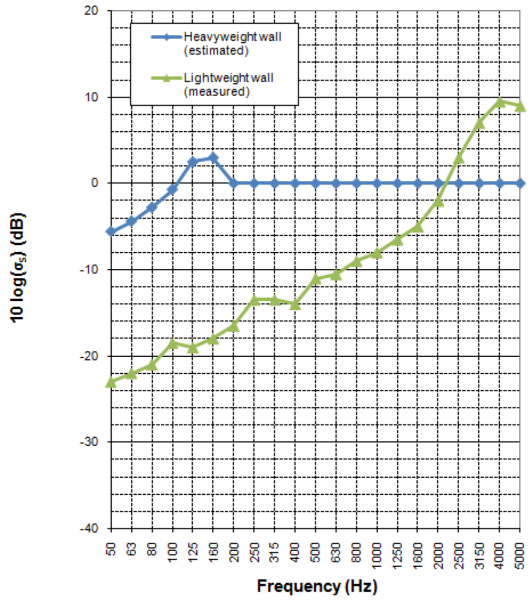

Figure 10: Radiation efficiency values considered

Validation laboratory measurements have been performed in the range 100-5000 Hz in the case of the concrete wall. The standard method presented in EN 14366 [2] was used. Calculation and test results as well as the associated A-weighted global values are shown in Figure 11.

Quite surprisingly, while velocity levels are higher in the case of the lightweight structure, the predicted structure-borne noises radiated by both types of walls are of the same order. The concrete wall radiates more noise at low frequencies, where most of the power is injected to the structure, because of its high radiation efficiency in the critical frequency region. In contrast, the lightweight wall has a very high critical frequency and low radiation efficiency values at low frequencies.

Although experimental and predicted results have quite similar shapes for the concrete wall, discrepancies up to 8 dB can be observed in the spectra and 4 dB(A) in global values. This could be attributed to uncertainties in the mobility approach as well as in the different assumptions used in estimating the different quantities

Due to practical issues, validation tests have not been carried out for the lightweight receiver. However, in situ measurements should soon be performed in the frame of another project, allowing comparisons between prediction and experimental results.

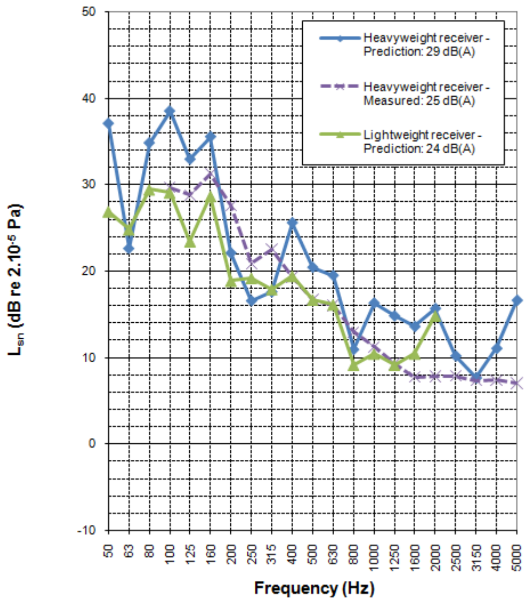

Figure 11: Predicted structure-borne noise - 2 l/s

5 Conclusion

A mobility-based prediction method for structure-borne noise generated by building service equipment was applied to the case of a waste water duct installed in heavyweight or lightweight constructions. Laboratory characterization measurements of the source and receivers were performed to obtain the required input data.

Prediction results showed that the high damping properties and low radiation efficiency of the lightweight structure compensate for higher power injected by the source. Consequently, structure-borne noise due to direct transmission to the adjacent room is not likely to be of more importance than in the case of a heavy concrete wall.

These results are subject to uncertainties and still need to be experimentally validated. Further work is considered to characterize other sources and receivers, both experimentally and by calculation.

Meanwhile, the mobility approach is under study within CEN/TC126/WG7 to yield a standard laboratory characterization method applicable to equipment installed in lightweight constructions.

Acknowledgments

This project has been funded by the CSTB Research and Development Department as well as the French ministry for Housing, Urban planning and Landscape (DHUP).

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