DOI: 10.61782/fa.2023.1139

forum acusticum 2023

Freshwater pipes as structure-borne sound sources: laboratory measurement and prediction

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ABSTRACT

Freshwater pipes are sources of structure-borne sound in buildings. Once the tap is opened the pipe system starts to vibrate and transmits sound through the contacts with the receiving structures. Usually pipe clamps form the contacts and manufacturers are interested in a method for product characterization that also provides input data for predictions in building situations. Laboratory measurements according to EN 15657 have been made on a test set-up that is based on ISO 3822. The blocked force has been determined that serves as input data for a prediction according to EN 12354-5 that has been validated by in-situ measurements in a building-like test stand. In addition, an insertion loss for pipe clamps without and with isolation measures was evaluated for both situations and it could be shown that the insertion loss can also be determined for excitation of the empty pipe with a miniature tapping machine.

Keywords: *structure-borne sound, installation noise, insertion loss*

1. INTRODUCTION

Noise from building equipment is a topic that has been addressed intensely by research work and standardization within the last two decades. Numerous case studies on various types of sources like e.g. whirlpool baths, lightweight stairs, heating devices and sanitary installations have been performed and led to the development of the test standard EN 15657 in 2009 that has been revised in 2017 to account for all installation conditions [1]. The methods for testing structure-borne sound sources have recently been applied by test institutes in a round robin which aimed to assess the uncertainty of the test methods to determine source quantities and the installed power [2]. The test results ac-cording to EN 15657 serve as input data for predictions of the sound propagation in buildings according to EN 12354-5 [3] that was recently revised and is almost ready for publication. The general methods in EN 15657 have been implemented in EN 14366-1 [4] for testing wastewater pipes and a current work item of CEN/TC 126 WG7 aims to develop a second part: 14366-2 for water supply installations. This standard should, like for wastewater, include installations with different components, not only different taps, but also different piping configurations and mounting elements.

In a recently started research project at the University of Applied Sciences Stuttgart, in collaboration with OTH Regensburg, TU Berlin and a manufacturer of pipe clamps, freshwater and wastewater systems are investigated. In this paper a case study on a freshwater pipe system, installed at a reception plate and in a building-like test stand is presented. Parallel work conducted on wastewater pipes is presented in [5].

2. MEASUREMENTS AT RECEPTION PLATE

Laboratory measurements according to EN 15657 have been made on a test set-up that is based on ISO 3822 [6]. The blocked force of a defined freshwater system has been determined that serves as input data for a prediction according to EN 12354-5. In addition, an insertion loss for pipe clamps without and with isolation measures at the pipe clamps was evaluated for excitation by water flowing through the pipe and for excitation by an electrodynamic miniature tapping machine (mini tpm).

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The idea for using the mini tpm (in Germany known as “Gösele-Kleinhammerwerk” and mainly used for K_{ij} measurements) was to reduce the effort for measuring the insertion loss of the pipe clamps due to the rubber inlay for a simpler product characterization.

2.1 Test Set-up

The test set-up is illustrated in Figure 1. A 1-inch freshwater pipe, made of galvanized steel with a total length of 2,5 m was connected to the vertical reception plate via two pipe clamps at Cp1 and Cp2. The distance between the contact points is 1 m. The pipe clamps (pairs without and with rubber) were screwed into metal expansion anchors that were inserted into the reception plate to provide a rigid contact. For fastening the pipe clamps on the pipe with a torque of 1,5 Nm (according to the guidelines of the manufacturer) a torque wrench was used. The pipe has two bends such that the vertical section of the pipe has a length of 2 m. On top of the pipe the Installation Noise Standard (INS) and other components according to EN ISO 3822 were installed (Figure 2). By a water supply system with a pump and other components a defined water flow through the pipe is produced. The water inlet is on the bottom, the outlet on top, both with flexible tubes. For the tests an operating condition with a flow pressure of 0,3 MPa was applied resulting (determined mainly by the INS) in a constant flow rate of 16,4 l/s. By additional measurements in the same operating condition with the pipe disconnected from the reception plate it could be ensured that airborne excitation of the reception plate is negligible in the installed condition.

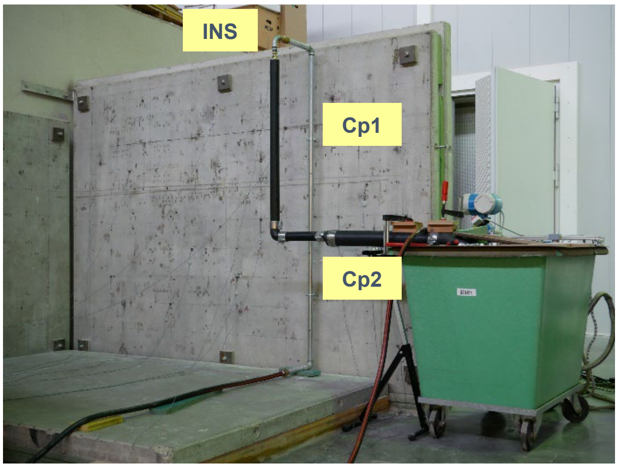


Figure 1. Test set-up for a 1-inch freshwater pipe made of galvanized steel connected to the vertical reception plate (isolated 10 cm thick reinforced concrete plate) via pipe clamps at two contact points (Cp1 and Cp2).

Figure 1: Installation Noise Standard (INS) and other components according to EN ISO 3822.

Figure 2: Pipe clamps used for fixing the pipe to the reception plate; left: with rubber inlay, right: without rubber inlay.

2.2 Blocked force according to EN 15657

The reception plate method according to EN 15657 is based on a power balance for stationary operating conditions. The power delivered from the structure-borne sound source into the reception plate is given by:

$$W_{\text{rec}} = \omega \cdot m \cdot \bar{\tilde{v}}^2 \cdot \eta \tag{1}$$

ω: angular frequency in rad/s

m: plate mass in kg

$\bar{\tilde{v}}^2$: spatially averaged plate velocity in $(m/s)^2$

η: total loss factor of the plate

Provided that a force source condition is given (true for the freshwater pipe and all other building equipment tested by HFT Stuttgart so far) the normalization to the averaged reception plate mobility at the contacts yields the single-equivalent blocked force of the source:

$$\tilde{F}_{\mathrm{b}}^{2} = \frac{W_{\mathrm{rec}}}{Re(\bar{Y}_{\mathrm{rec}})} \tag{2}$$

$\tilde{F}_{\mathrm{b}}^{2}$: source single equivalent blocked force in N^2

$\bar{Y}_{\mathrm{rec}}$: plate mobility averaged over the contacts in m/Ns

The source blocked force serves as input data for predictions using EN 12354-5. It was evaluated for the excitation with water flowing through the pipe.

2.3 Insertion loss

From the spatially averaged reception plate velocity levels without and with isolation measures an insertion loss can be evaluated:

$$\Delta L_{\mathrm{v}} = L_{\mathrm{v},0} - L_{\mathrm{v},1} \tag{2}$$

$L_{\mathrm{v},0}$: spatially averaged reception plate velocity level without isolation

$L_{\mathrm{v},1}$: spatially averaged reception plate velocity level with isolation

The insertion loss quantifies the improvement due to isolation measures, here: due to the rubber inlay in the clamps, and serves as quantity to describe product characteristics. It was evaluated for the excitation due to water flowing through the pipe and for excitation with the mini tpm.

2.4 Measurement results for excitation by water flow

In Figure 4 is shown the spatially averaged reception plate velocity (for 12 accelerometer positions) resulting from water flow through the pipe without and with rubber inlay in the pipe clamps in narrow bands and converted into 3rd octave bands. The background noise level is also shown. Except for the very low frequencies the levels are well above background noise. The velocity levels in narrow bands show distinct peaks and dips that result primarily from Eigenmodes of the reception plate and the pipe. The Eigenmodes of the reception plate are seen in the measured contact mobilities in Figure 6 whereas a detailed study of the pipe e.g. by an experimental modal analysis or FE simulation as for the wastewater pipe in [5] has not been done yet but is intended. Up to 400 Hz the levels without and with rubber inlay are similar. An improvement by the inlay is observed above 400 Hz but the increase of the insertion loss (Figure 5) with frequency is not constant as could be expected. A peak value of 18 dB is observed at 1250 Hz but then a plateau follows.

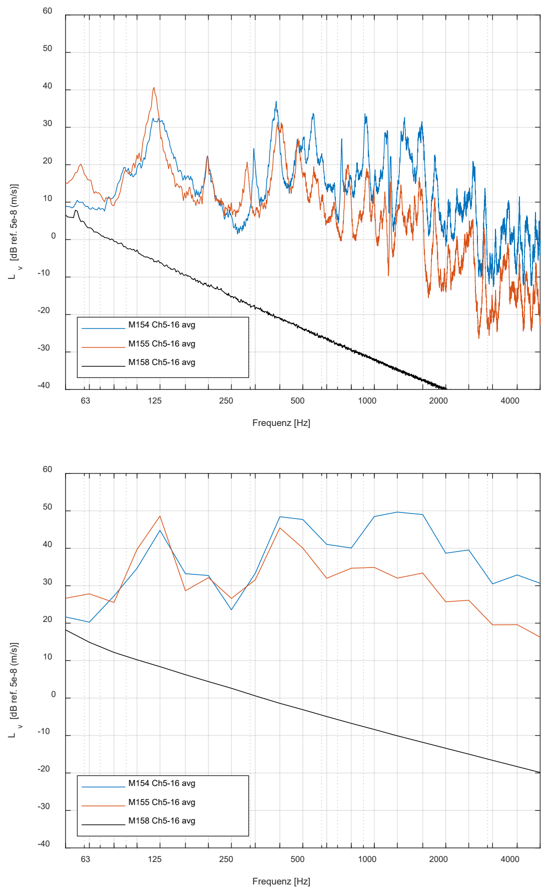


Figure 3: Spatially averaged reception plate velocity levels for excitation with water flow; blue: pipe clamps without rubber inlay, red: pipe clamps with rubber inlay; black: background noise level.

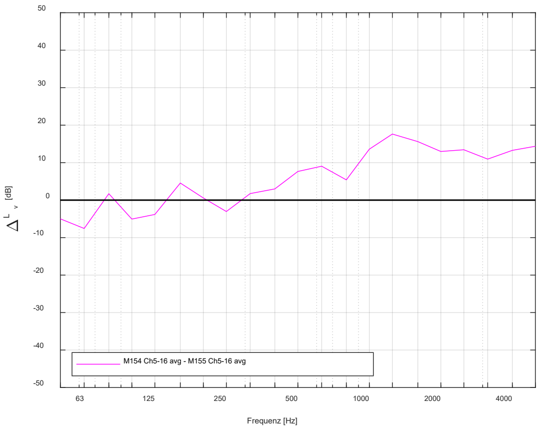


Figure 4: Insertion loss by the rubber inlay in the clamps for the excitation of the pipe by water flow in 3rd octave bands.

In Figure 6 are shown the reception plate mobilities with the pipe removed, at the contacts with the pipe. The peaks correspond to the Eigenmodes of the plate and indicate a high receptiveness for excitation. Figure 7 shows the blocked force of the pipe system where the influence of reception plate modes is eliminated due to the normalization to the plate mobility. Most of the peaks in Figure 4 are still there which indicates that the modal characteristics of the pipe system have a strong effect on the transmission. This was also assumed from experimental results with different configurations of a freshwater pipe installed to the reception plate in [8].

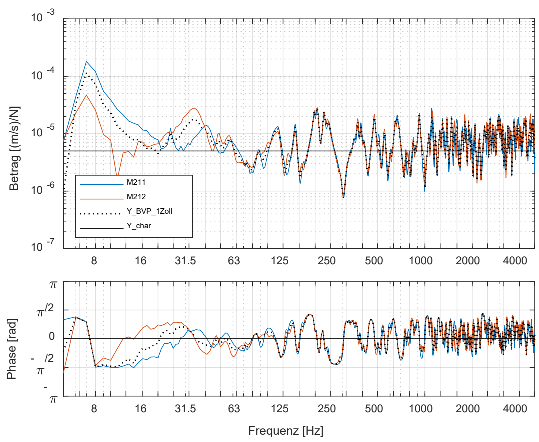
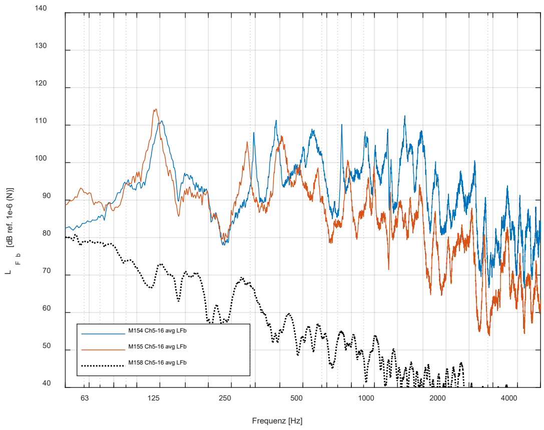


Figure 5: Single-equivalent mobility of the reception plate at Cp1 and Cp2 and averaged.



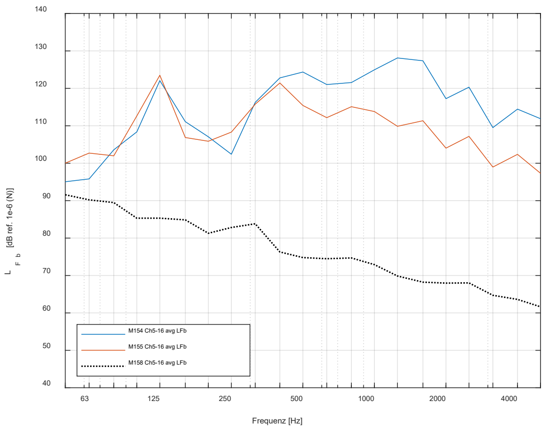


Figure 6: Blocked force of the pipe for excitation with water flow; blue: pipe clamps without rubber inlay, red: pipe clamps with rubber inlay.

2.5 Measurement results for excitation with mini tpm

In Figure 9 is shown the spatially averaged reception plate velocity resulting from excitation of the empty pipe at the first of totally 8 excitation positions: 4 in direction perpendicular to the plate and 4 parallel to the plate (Figure 8). The results in narrow bands show a 10 Hz line spectrum corresponding to the impact frequency of the one steel hammer that has roughly a 21 dB smaller blocked force spectrum than the ISO tapping machine. In Figure 10 the plate velocity levels resulting from water flow and from excitation with the mini tpm at 4 positions perpendicular to the plate are compared. The spectral shape and the magnitude of order for water excitation and with the mini tpm are quite similar. It is worthwhile noticing that the INS is, as indicated by previous investigations, primarily a fluid-borne sound source [7], [8], while the mini tpm is a pure structure-borne sound source. Obviously the "secondary structure-borne sound" [7], [8] caused by conversion of the fluid-borne sound from the INS is similar as for excitation of the empty pipe with the mini tpm. Figure 11 shows the same comparison but for the excitation in parallel to the plate. Here the water flow causes a roughly 10 dB stronger excitation at the contact points than the mini tpm.

For the excitation with the mini tpm the insertion loss was evaluated for each excitation position and then averaged and compared to the result with water excitation. The good agreement for both, shown in Figure 12, is promising regarding a simplification of the test procedure when only the insertion loss e.g. of pipe clamps or anchors is to be evaluated. It could be expected that averaging over more than 8 excitation positions (also other excitation angles) with the mini tpm would lead to an even better agreement. It is intended to analyse this more detailed by means of FE simulations.

Figure 7: Excitation of the empty pipe with miniature tapping machine at pipe position 1; left: excitation perpendicular to the plate, right: excitation parallel to the plate.

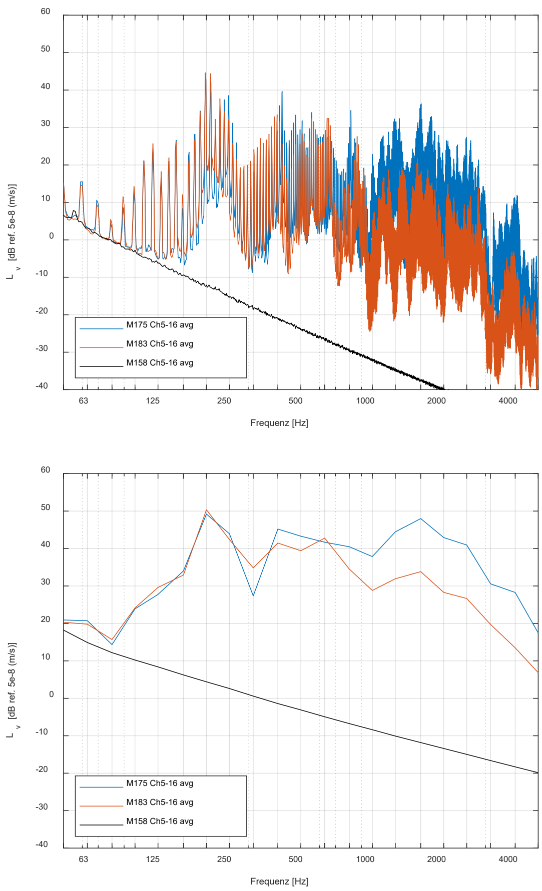


Figure 8: Spatially averaged reception plate velocity levels for excitation with mini tpm at pipe position 1 perpendicular to the plate; blue: pipe clamps without rubber inlay, red: pipe clamps with rubber inlay.

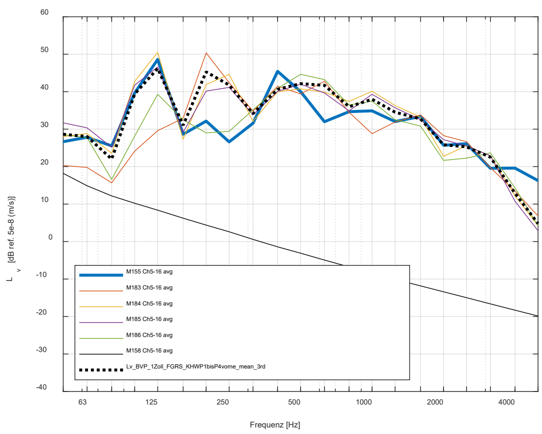


Figure 9: Spatially averaged reception plate velocity levels for excitation with water (blue curve) and mini tpm at 4 positions perpendicular to the plate and averaged (black dotted curve) for the installation with the pipe clamps with rubber inlay.

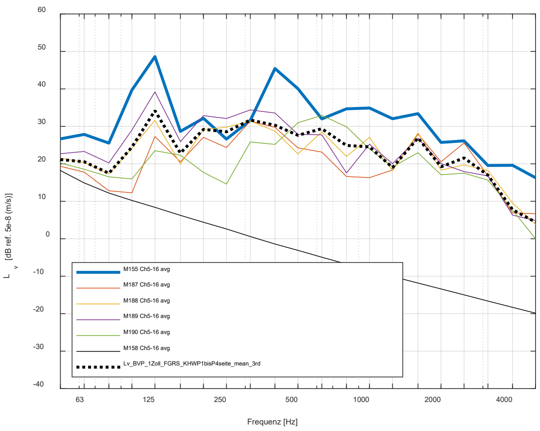


Figure 10: Spatially averaged reception plate velocity levels for excitation with water (blue curve) and mini tpm at 4 positions parallel to the plate and averaged for the installation with the pipe clamps with rubber inlay.

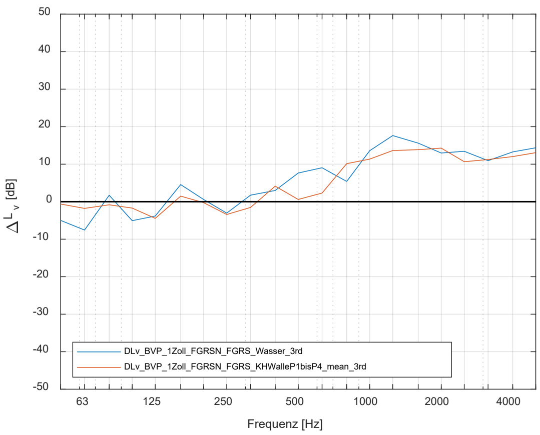


Figure 11: Insertion loss by the rubber inlay for the excitation of the pipe by water flow (blue curve) and by the mini tpm (red curve), averaged over all 8 excitation positions, in 3rd octave bands.

The insertion loss from the A-weighted sum levels of the measured sound pressure levels, as outlined in the next section, is 6,6 dB. This “single-number” quantity is used by manufacturers for marketing. It can only be determined from sound pressure level measurements in the installed condition or from predictions of the sound pressure levels with the blocked force and EN 12354-5 but not directly from measurements on the reception plate.

3. MEASUREMENTS IN BUILDING SITUATION

The same test set-up was installed in the ground level of a building-like installation test stand that is also used for measurements according to EN 14366-1 (Figure 13).

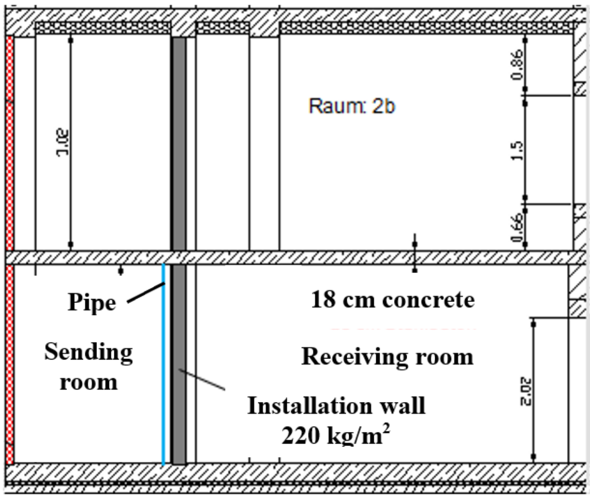


Figure 12: Test set-up from Figure 1 installed in a building-like test stand with a 11,5 cm thick plastered installation wall made of CaSi bricks and a surface mass of 220 kg/m^2.

The velocity on the installation wall and the sound pressure level in the receiving room for horizontal transmission were measured simultaneously, again for excitation with water flow and the mini tpm (results not shown here). In Figure 14 are shown the spatially averaged velocity levels on the installation wall resulting from water flowing through the pipe without and with rubber inlay in the pipe clamps. Figure 15 shows the same comparison for the sound pressure levels. The spectral shape of the narrow band results for the sound pressure levels exhibit less distinct peaks due to the coupling of structural modes and room modes. After conversion into 3rd octave bands velocity levels and pressure levels are very similar which means that the evaluation of the insertion loss gives the same result. This offers a choice for laboratories to measure the insertion loss “in-situ” either by velocity or sound pressure measurements.

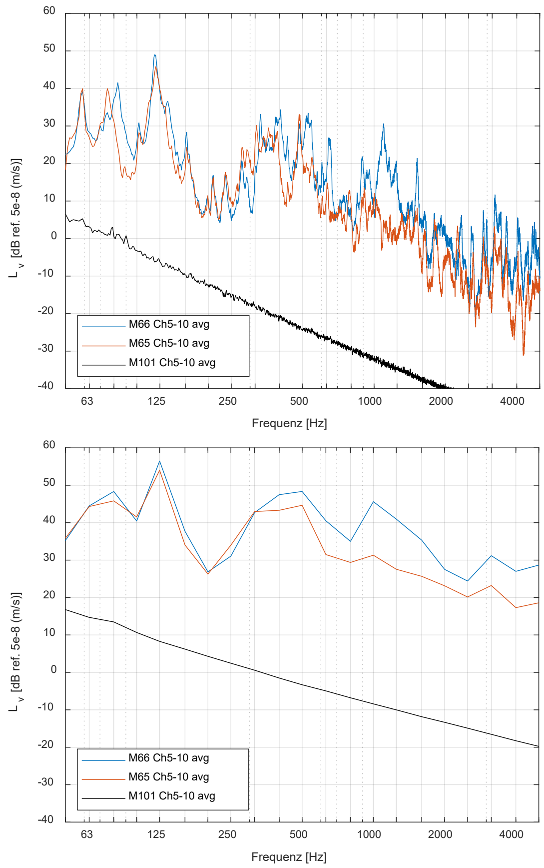


Figure 13: Spatially averaged velocity levels on the installation wall for excitation with water flow; blue: pipe clamps without rubber inlay, red: pipe clamps with rubber inlay; black: background noise level.

In Figure 16 the results for the insertion loss from measurements at the reception plate an “in-situ” in the building-like test stand are compared. Up to 1 kHz the agreement is good, above 1 kHz the in-situ measurement gives lower values. So far, the reason for this is not clear and further investigations, e.g. on the effect of the metal expansion anchors and their installation, are intended.

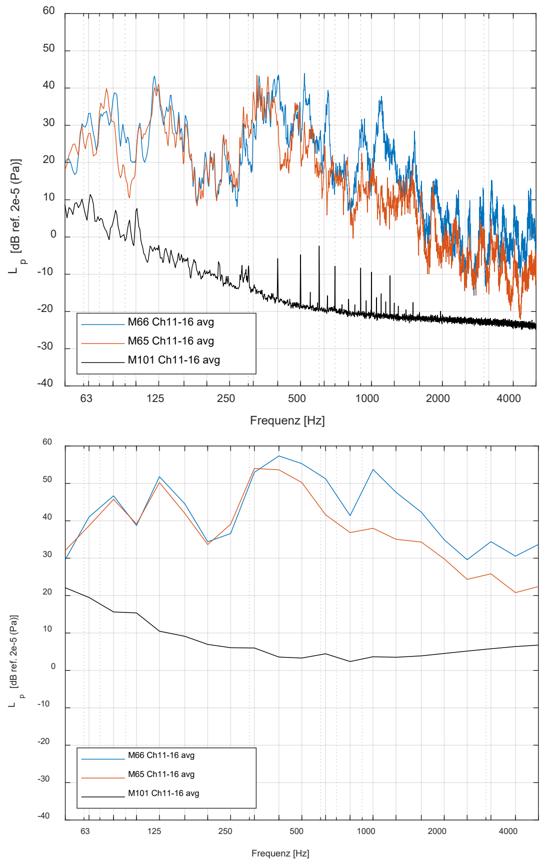


Figure 14: Spatially averaged sound pressure levels in the receiving room for excitation with water flow; blue: pipe clamps without rubber inlay, red: pipe clamps with rubber inlay; black: background noise level.

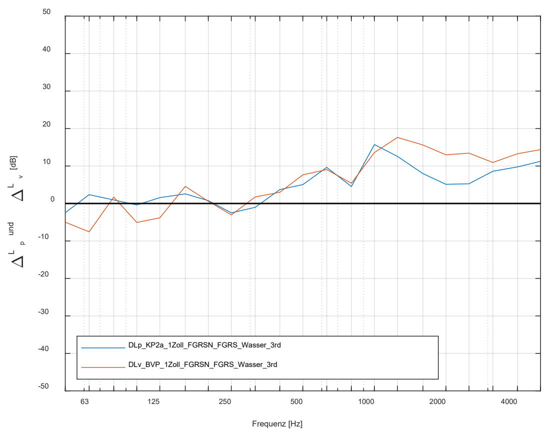


Figure 15: Insertion loss by the rubber inlay

measured at reception plate and in the building-like test stand evaluated from sound pressure measurements.

4. PREDICTION FOR BUILDING SITUATION

With the blocked forces from the reception plate method the A-weighted normalized sound pressure level in the receiving room was predicted according to EN 12354-5:

$$L'_{\mathrm{ne,s,i}} = L'_{\mathrm{n,i}} + L_{\mathrm{Fb,eq}} - L_{\mathrm{Fb,eq,stm}} \tag{3}$$

$L'_{\mathrm{n,i}}$: apparent impact sound pressure level of element i calculated according to EN 12354-2, or measured on site if the building exists

$L_{\mathrm{Fb,eq}}$: single equivalent blocked force level in dB ref. 10^{-6} N of the source, measured according to EN 15657

$L_{\mathrm{Fb,eq,stm}}$: single equivalent blocked force level in dB ref. 10^{-6} N of the ISO tapping machine calculated from literature

The comparison of measurement and prediction of the A-weighted normalized sound pressure level in the receiving room for the installation with pipe clamps with rubber inlay is shown in Figure 17. Except for the frequency range below 100 Hz where the diffuse sound field assumption doesn't hold true the agreement is good. The maximum values occur around 500 Hz. The sum levels are 50,4 dB in measurement and 49,2 dB in prediction. These values may not be compared to requirements such as $L_{\mathrm{AF,max,n}} \leq 30$ dB for living rooms in Germany as the INS is a much stronger source than usual taps or valves.

5. CONCLUSIONS

A case study in order to characterise a freshwater pipe system in the laboratory according to EN 15657 has been conducted. The blocked force obtained was used to predict the sound transmission in a building-like test stand using EN 12354-5 with good agreement. Thus, it is shown, that the methodology to handle building equipment in terms of laboratory characterisation and prediction, can also be used for freshwater pipe systems. Moreover, an insertion loss for pipe clamps was evaluated that can be used for product comparison and to rate isolation measures.

6. ACKNOWLEDGMENTS

The authors are grateful to the Federal Ministry of Education and Research (BMBF) and fischerwerke GmbH & Co. KG for their support.

7. REFERENCES

[1] EN 15657:2017: Acoustic properties of building elements and of buildings - Laboratory measurement of structure-borne sound from building service equipment for all installation conditions.

[2] Wittstock, V., Scheck, J., Villot, J-M.: Structure-borne sound sources in buildings – Estimating the uncertainty of source properties and installed power from interlaboratory test results. Acta Acustica, Vol. 6, 16 (2022).

[3] EN 12354-5:2023: Building acoustics - Estimation of acoustic performance of building from the performance of elements - Part 5: Sound levels due to the service equipment (Document distributed for enquiry to the European countries represented in CEN TC 126).

[4] EN 14366-1:2023: Laboratory measurement of airborne and structure-borne sound from service equipment - Part 1: Application rules for waste water installations; German and English version prEN 14366-1:2022.

[5] Däuble, L., Scheck, J., Zeitler, B.: Wastewater pipes as structure-borne sound sources: laboratory measurement and finite element analysis, Proc. Forum Acusticum Torino, 2023.

[6] EN ISO 3822-1:2009: Acoustics - Laboratory tests on noise emission from appliances and equipment used in water supply installations - Part 1: Method of measurement (ISO 3822-1:1999 + Amd 1:2008).

[7] Fischer, H.M.: Describing Noise of Water Appliances by ISO 3822: What happens really?, Proc. CFA/DAGA, 2004.

[8] Alber, T., Fischer, H.M., Gibbs, B.: Fluid-structure interaction in domestic piping systems, Proc. DAGA, 2007.