Sanitary Installations in Buildings – Noise Contribution Analysis with Sensor Arrays and Laser Scanning Vibrometry

Oliver Wolff
Department of Building Physics, GEBERIT, Jona, Switzerland.
Joachim Förster
Department of Building Physics, GEBERIT, Jona, Switzerland.
Rolf Weiss
Department of Basic Sanitary Technologies, GEBERIT, Jona, Switzerland.

Summary
A new method combining CFD simulations, laser scanning vibrometry and sensor arrays for sanitary noise applications is used to analyze and visualize the acoustic contribution of the relevant components of a sanitary installation to the overall installation noise. The pipe work contributes to appr. 50% of the overall noise, the rest is due to the remaining elements of the installation system. This statement applies to solid walls and light weight systems in the same way. The results are visualized in time domain and in frequency domain.

1. Introduction and Aim of Study

Noises from sanitary installations in buildings are often considered annoying. A reason might be, that sound cannot be judged by its measured sound pressure level only. Instead, sound is a flow of information that travels from an activated system towards a listening person with individual feelings and personal expectations. As such, noises created by the sanitary systems from neighbours might be perceived unnecessary or annoying, even in cases of low sound pressure level.

Most of the sounds in building acoustics can be treated by theoretical models which are described in acoustical standards. Especially the standard EN 12354-5 [1] allows the theoretical calculation of sound pressure levels in buildings. However, sanitary installations are not well represented in this standard as a fully validated acoustical model to predict sanitary installation noises in buildings does not exist so far.

Sound generated by sanitary systems are difficult to model because the sound is created by a complex interaction of various acoustically relevant elements such as pipes, ceramics, cisterns, studs, plasterboards, etc. and their direct or indirect connection to the building.

In addition, contributions from structure borne and airborne sound are intermixed with each other and even worse, the interaction of the participating elements is time dependent.

The presented study shows the analyses and visualization of various sound paths and their contributions generated by a sanitary installation. A special technique has been used combining multichannel sensor arrays with laser scanning vibrometry. The study analyses the sound paths for light weight constructions and solid constructions.

The aim of this study is related to the current situation of the “standard’s landscape”.

The dependencies for sanitary installation noise can be illustrated in the following Figure 1. The ISO/DIS 19488 standard “Acoustic classification of dwellings” [2] defines different levels of acoustic
comfort in dwellings. Six classes are specified, class A is the highest and F is the lowest class. As the standard is not subjected to the “Vienna agreement”, the application to national law is optional. However, this ISO standard has a significant influence on the perception of stakeholders, especially for buyers and sellers of housings.

![“Standard’s Landscape”](image)

Figure 1. Sanitary installation noise within the “Standard’s landscape”.

The national regulations (DIN, SIA, ÖNORM, etc.) refer to some extent to the European standard EN 12354-5. This standard is intended to lay the foundation for acoustic simulation of sanitary installations. Unfortunately, the underlying theoretical concept is not complete and can therefore only be used as an orientation, so far.

One of the main issues is the lack of experimental input data for the prediction model. The standard EN 15657 [3] describes a test device called “Reception Plate” that allows to gather the needed input data for the standard EN 12354-5.

Waste water pipes are considered as main noise contributors to the overall installation noise. An important standard in this respect is EN 14366 [4].

Even though the standard EN 14366 is often used to judge sanitary noises, it can only be applied to straight pipes and cannot fully predict the sanitary noises in real buildings.

The EN 14366 standard is currently under revision. The intention is to create a link from this standard to the reception plate standard EN 15657 to provide input data for noise prediction models used in EN 12354.

The question is, if this approach is sufficient. The presented study focusses on the questions: To what extent do waste water pipes (EN 14366) and the rest of the sanitary installation system contribute to the overall installation noise? Is there a difference between light weight and solid constructions?

The study will also shed some light on the correlation between water flow in waste water pipes and the corresponding emission of noise and its relation to the influence of turbulent kinetic energy.

The experiments of this study where performed on room height, light weight installation walls, made of metal studs and plaster boards.

It might be worthwhile to note, that solid installation walls have been already investigated in a previous study [5]. For the purposes of completeness, the main statements of this previous study are also presented in this survey.

2. Experiments

2.1 Setup and test objects

The tests were performed in the building physics lab of Geberit in Jona, Switzerland. The Figure 2 shows the general measurement set up. Four rooms are involved. The installation room is the room where the excitation takes place, initiated by pressing the flush button (room 12). The vertical room (room 11)
is equipped with the same sanitary installation as used in the sending room. Assuming common planning conventions, the vertical and horizontal rooms (MR 11 and MR 08) are usually rooms with low noise protection, e.g. bathrooms. The diagonal room (MR 07) could be a noise protected room e.g. a bedroom or a dining room and is therefore of highest importance. The measurements were taken in the diagonal room.

A sensor array with 36 accelerometers and 3 “Low Noise” microphones were used. The sensor array was applied 3 times to fully cover the area of interest of the installation wall.

The multichannel data acquisition system and postprocessing software was procured from the company HEAD acoustics. The Laser Scanning Vibrometer of type “PSV500” was acquired from the company “Polytec”.

The test object was a room height, light weight installation wall, based on metal studs and plasterboard and equipped with sanitary installations (Figure 3).

Three different variations were investigated: 1) original standard configuration 2) Sanitary system separated and decoupled from the installation wall with connection via rigid waste water pipe. 3) Sanitary system separated and decoupled from the installation wall with connection via soft tube used as waste water pipe.

In a previous study [5] a part height, light weight sanitary prewall system in front of a solid wall has been investigated. The test setup and the tested variation are shown in Figure 4.

2.2 Measurement concept

Laser scanning vibrometers enable accurate measurements of surface velocities. However, as only one laser beam is used per measurement point a triggered excitation is often necessary. Otherwise, the phase relationship among the measurement points is lost. Sanitary noises typically consist of transient signals where phase relationships play an important role. To initiate a separate flush for every single measurement point might be quite

Figure 3. Different test setups for a light weight construction.

Figure 4. Different test setups for a light weight prewall in front of solid wall.

Original installation with (C-M1) and without foam decoupler (C-M3), waste water pipe made of soft tube (C-M5), sanitary installation separated from prewall, waste water pipe as soft tube (D-M1) and with rigid pipe (D-M3).
cumbersome, especially because no single flush is exactly reproducible. To circumvent this difficulty an array of accelerometers has been used (Figure 5).

Figure 5. Positioning of sensor array on the wall.

The laser scanning vibrometer is used in a first step to create dummy data. These data are then replaced by the post processed data of the accelerometer array and in a second step visualized in the laser scanning software (Figure 6).

Various visualization possibilities exist in time and in frequency domain (Figure 7):
- Level versus time
- Amplitude of certain frequency at a certain point in time
- RMS-values for selected frequency bands over preselected time periods, etc.

Figure 7. Visualization options.

The array was positioned in the diagonal room. Three walls were considered, see Figure 8, top (ceiling), left (side wall), right (wall below installation wall).

Figure 8. Selection of surfaces.

2.3 Validation of concept

Four main assumptions have been made:

1) The array is uniformly spread over the surface.
2) Radiation factor is one.
3) Main contributing surfaces have been captured.
4) Room acoustic effects are ignored.
By making these four assumptions, the following formula (1) can be deduced [5].

\[
\int \tilde{a}_{\text{Surface}} \cdot dt = \tilde{v}_{\text{Surface}}
\]

\[
\sqrt{\tilde{v}_{\text{Surface}}^2} = \sqrt{\frac{P_{\text{Air}}}{\sigma \cdot \rho_0 \cdot c_0 \cdot S}} = \approx \sqrt{\frac{P_{\text{Air}} \cdot \tilde{p}_{\text{Air}}}{\sigma \cdot \rho_0 \cdot c_0 ^2}} = \text{const} \cdot \tilde{p}_{\text{Air}}
\]

\[\text{(1)}\]

\(\tilde{a}_{\text{Surface}}\) = area averaged surface acceleration

\(\tilde{v}_{\text{Surface}}\) = area averaged surface velocity

\(P_{\text{Air}}\) = radiated sound power in air

\(\sigma\) = radiation factor

\(\rho_0\) = density of air

\(c_0\) = sound velocity in air

\(S\) = surface area

\(\tilde{p}_{\text{Air}}\) = space averaged sound pressure

This equation links the surface vibration of the wall with the resulting sound pressure in the room.

To check that the main contributing surfaces are covered by the array, an experimental comparison between the measured sound pressure level (microphone) and the surface velocity (acceleration sensors) has been made for the original state. The A-weighted surface velocity contributions of the three measured surfaces indicated in green, red and blue are plotted in Figure 9 and compared to the level versus time diagram of the microphone data.

The green curve shows the biggest contribution (wall below installation wall). The other two walls (blue and red) do not contribute in a significant way. Even though the level versus time plot of the microphones coincides reasonably well with the array data for \(t > 4\) sec, the first peak at \(t = 2\) sec is not represented appropriately. It seems, that the sensor array does not fully capture the noise emission of this first peak. This result has been found previously for light weight prewall systems in front of solid walls as well [5].

The reason for this discrepancy will become clearer in the context of the CFD simulation.

### 2.1 Test results

The test results are visualized in two ways, level versus time or rms values for predefined frequency bands and predefined time periods.

Figure 10 shows the original installation in terms of level versus time for different snap shots. The waste water pipe is installed on the left side behind the wall. The green colour indicates the increased vibration level in this area.

Figure 11 shows the vibration levels for different frequency bands for the first peak (left side of diagram) and the second peak (right side of diagram).

The lowest graph shows the average over the whole frequency range from 20 Hz to 5 kHz.

The vibration excitation for the first peak is pronounced in the upper part of the wall while the excitation pattern for the second peak has contributions on the left side of the wall, especially at the contact points of the two pipe clamps.
Figure 10. Snap shots for level vs. time.

The blue and black curve in Figure 12 indicate the decoupled installation (in this case only the waste water pipe contributes). The red and green curve indicate the coupled installation instead. It can be concluded that the contribution of the waste water pipe to the overall installation level $L_{AF,max,n}$ (second peak) is appr. 2-3 dB. Expressed in percentage this would be almost 50 %.

Figure 12. Snap shots for level vs. time.

This means that both parts, the waste water pipe and the sanitary installation system (metal stud frame, ceramic, cistern, etc.) contribute approximately to the same extent.

The same proportion of contributions could be measured for the solid wall installation as well [5].

Another test was done with full flush (6 liter) and reduced flush (3 liter). The change from full flush to reduce flush leads to an increase of the second peak, see Figure 13.

Figure 13. Appearance of peak for reduced flush.
The origin of this peak appearance will be discussed in the following CFD simulation part.

3. CFD Simulations

Where does the water flow when it is getting loud? This apparent easy question is difficult to answer. CFD simulation was performed to help understanding the water flow inside pipes in more detail and its effect to the emitted installation noise. Figure 14 visualizes the water flow and the emission of noise for a full flush. The left part of Figure 14 depicts a snapshot at t = 0.85 seconds after initiating the flush. The sound pressure level inside the room is maximum at this point, indicated by the cursor position in the graph (first peak). Even though the water is still inside the ceramic and has not entered the pipework yet, the measured surface velocity shows a maximum at the bottom of the wall. It is a remarkable result, that the excitation is not maximum at the top of the wall where the sanitary installation is located. For whatever reason, this vibration is driven by structure borne excitations of the sanitary system consisting of cistern, ceramic, metal studs, plasterboard panels, etc. and not by the waste water pipe.

On the right side of this Figure 14 the snap shot is taken at t = 5.35 seconds (second peak). This peak is relevant for \( L_{AF,\text{max},n} \) determination. Most of the water is already inside the pipe and has reached or even passed the wall of the receiving room. The link between water flow and sound radiation can be clearly seen. In this case the pipe contributes to the noise creation in the receiving room. However, as stated previously, the contribution from the pipe work to the overall installation level is only appr. 50%. The other 50% contribution is due to the rest of the installation system. The two maxima on the left side of the wall (dark green spots) might be ascribed to the sound injection into the wall via the two pipe clamps.

Figure 15 visualizes the water flow and the emission of noise for a reduced flush. The reduced flush shows at t = 1.05 seconds (first peak) a similar picture compared to the full flush. Also in this case, the main excitation takes place at the lower part of the wall. The closing valve induces a significant noise impact at 2.75 seconds, see right part of Figure 15.

Even though the water has not fully entered the down pipe yet, the vibration at the bottom of the wall reaches a maximum. This indicates that the installation system induces structure borne sound into the building structure. The reason, why the excitation is high on the lower part of the wall and not on the upper part remains unclear. In any case, it is not the pipe work that contributes to this noise peak.

It is illustrative to have a look at the evolution of noise generation and the corresponding flow of water. The left picture of Figure 16 shows the noise level versus time for full flush (green curve) and reduced flush (red curve). The dotted curves show the volume flow accordingly. The maximum volume flow for full flush and reduced flush are the same. The question is: Why is the broad second peak of the full flush higher than the reduced flush? If volume flow is the only driver for noise emission, the maximum sound pressure level should be the same. The explanation can be deduced from the right picture of Figure 16 where the turbulent kinetic energies are displayed (dotted curves). The turbulent kinetic energy yields higher values for the full flush compared to the reduced flush. The main driver for noise creation is therefore the turbulent kinetic energy and not the volume flow.

4. Conclusions

The presented method combines laser scanning vibrometry with sensor array measurements. The validity of the method could be shown for both, light weight and solid building constructions. The sound pressure level contribution from the pipe work to \( L_{AF,\text{max},n} \) amounts to appr. 50%, the other half originates from the remaining elements of the sanitary installation system (cistern, metal studs frame, ceramic, filling valve, flushing valve, etc.). For reduced flushes (e.g. 3 liter) the closing of the flushing valve can lead to high noise level peaks. Turbulent kinetic energy is the key driver for pipe noise creation, volume flow is secondary. The first peak in the level versus time diagram of the installation noise is due to the excitation of the building structure at the bottom of the installation wall in the receiving room.

5. Outlook

EN 14366 is currently under revision for matching with EN 15657 and EN 12354-5 input quantities. However, EN 14366 focusses on the acoustic contribution of straight pipes only. In order to fully predict the overall installation noise an inclusion of
every sanitary installation component is necessary. The contribution from sanitary installations could possibly be assessed by performing measurements using the reception plate method (EN 15657). These input data could then be used by the prediction model described in EN 12354-5.

References

Figure 14. Visualization of full flush.

Figure 15. Visualization of reduced flush.

Figure 16. Volume flow and turbulent energy.