Experimental Investigation of the Governing Vibration Excitation Mechanism in Wastewater Pipe Systems

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Abstract

Structure-borne sound of wastewater pipe systems often dominates the noise from sanitary installations in buildings. The drainpipe system is composed of several pipe elements, (1) straight cylindrical section, (2) inlet (T-joint), and (3) bend. When water flows through a pipe system, the vibration is excited by the water fall at the inlets and the bend, and by the turbulent water flow adhering to the inner wall of the pipe elements. The vibration is transmitted to building elements via fixing elements like pipe clamps. This study aims to experimentally investigate the dominant vibration excitation with reference to the flow rate and frequency. The physical arrangement of the pipe system is based on the set-up given in standard DIN EN 14366:2020-02 [1], and further modified to focus on a single excitation source. A total of five different pipe arrangements were tested with four different flow rates. The vibration response of the pipe was evaluated in terms of the blocked force at the fixing point on the wall. The experimental results indicate that the dominant excitation source is dependent on the flow rate. The significance of the flow-induced force on the bend increases with the flow rate.

Introduction

The wastewater noise is often a problem in adjacent rooms in buildings. Noise from wastewater systems is generated by the turbulent water flow and the waterfall hitting the water inlets, tees and the bend. These geometrical discontinuities cause structure borne vibrations on the pipe wall and the system itself. Due to the connection of the pipe system to the installation wall with fixing elements, like pipe clamps, the vibrations are led into the building structure, and consequently, radiated as airborne sound.

Several acoustically designed pipe components are already available in market to supress the noise emission from the wastewater pipes: e.g., a heavy, rigid basement bend or specially shaped inlets to guide the water flow. The basement bend element made of a rigid material (concrete) helps to suppress the vibration excitation by the water fall at the bend. The inlet component with the water guide is designed to control the flow into the pipe such that the impact due to incoming water is reduced. These treatments are efficient only if the treated component is exactly the dominant excitation source of the drainpipe system. Instead, increase of the weight of the pipe system is in general very effective to supress noise [2]. However, this solution is not only production cost inefficient, but also environmentally unfriendly [3]. To develop new products towards eco-design without deteriorating the noise emission, it is important to investigate the vibration excitation mechanism with reference to the flow rate and frequency.

Physical Arrangement

Test Facility

Figure1 shows the wastewater systems set-up at the Fraunhofer Institute for Building Physics in Stuttgart. The pipe is made of PP-MD (polypropylene with mineral additives, 1.7 kg/m^3) with the outer diameter of 110 mm, and the wall thickness of 3.2 mm. The steel pipe clamps with rubber inserts connect the pipe to the installation wall with M10 screws.

The measurements are performed according to DIN EN 14366 [1] with the constant volume flows of 0.5, 1.0, 2.0, and 4.0 L/s. It must be noted that the drainpipe is not filled with water, rather the mixture of water and air under these volume flow rates. The running water adheres to the inner wall of the pipe elements, while the air flows continuously in the centre of the tube.

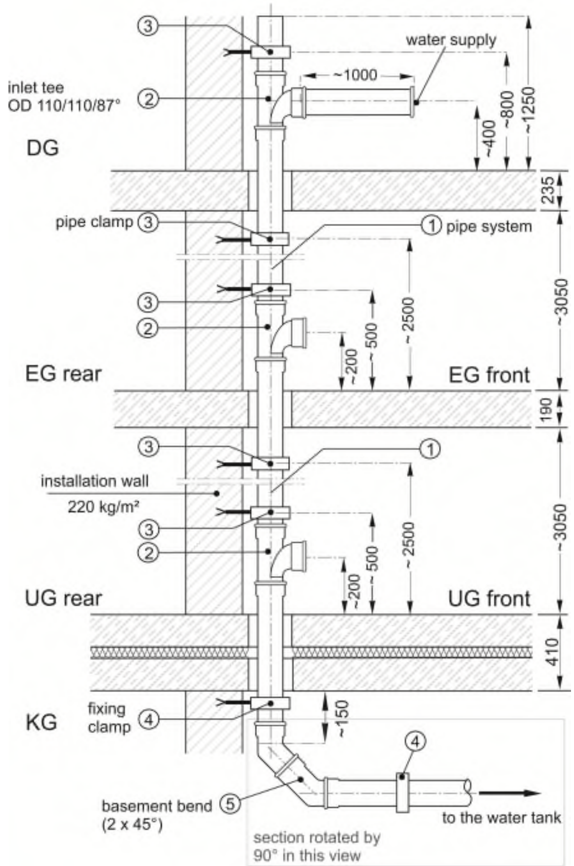

Figure 1: Test facility with the standard wastewater system set-up at IBP, Stuttgart for measurements according to DIN EN 14366 [1].

The test facility is specially designed for measuring very low sound levels and can be used to test all types of domestic installations under practical conditions. The installation wall in the test facility has a surface density of 220 kg/m² and thus corresponds to the lightest single-shell solid wall permitted for mounting sanitary installations according to the German Standard DIN 4109 without special proof of suitability. These wall properties also comply with the specifications of DIN EN 14366 [1]. The noise is measured in the receiving rooms on the ground floor ('EG rear' in Fig. 1) and the underground floor ('UG rear' in Fig. 1).

Pipe Arrangement

As shown in Figure 1, the standard pipe system extends over four floors. The system consists of the straight pipes with the water inlet in the attic, two tees (closed by a lid) on the ground and the underground floors, and the bend with 90-degree angle in the basement. The excitation sources of this pipe are separated into the following four components: (1) turbulent water flow, (2) impact force at the water inlet, (3) water fall at the tee in the ground and underground floors, and (4) water fall on the basement bend. The effect of acoustic waves inside the pipe generated by the vibration of the pipe wall and the turbulent flow is ignored in this study.

Table 1: Tested wastewater system configurations

Name		Tee in EG	Tee in UG	Bend
#1	Standard	attached	attached	attached
#2	Straight	--	--	--
#3	Tee in EG	attached	--	--
#4	Tee in UG	--	attached	--
#5	Bend	--	--	attached

Figure 2: The nominal basement bend replaced by a larger diameter.

To focus on each of those excitation sources, the pipe arrangement needs to be modified from the standard setting. Table 1 summarizes the tested five configurations of the pipes. The 1st configuration is the standard model (shown in Figure 1) with all excitation sources, while the "straight" drainpipe, the 2nd configuration, is composed of the water inlet and the straight cylindrical components only. The tees are replaced by straight cylindrical pipes with the same length, and the basement bend is decoupled from the system. The water falls on a bend with a larger diameter than the pipe system, such that the bend has no physical contact to the upper drainpipe (see Figure 2). Under this configuration, the straight pipe is excited only by (1) the turbulent flow and (2) the impact force on the water inlet, which cannot be eliminated from the system. The 3rd and 4th models are composed on the straight pipe with a tee on the ground or underground floor, respectively. The 5th model consists of the straight model with the coupled basement bend.

Experiments

Blocked Force

Since wastewater systems are only connected to the installation wall via the six clamping points, the vibration response of the pipe was evaluated in terms of the force at the contact points. The power substitution method was applied to indirectly determine the blocked force in terms of RMS values using the measured sound pressure levels in the receiving rooms and the pre-determined transfer function of the test facility [4]. In the ground and the underground floors, the pipe is fixed to the wall via two clamps with the distance of 2 m. The single equivalent blocked force on one floor, $L_{Fb,eq}$, was obtained as the sum of the RMS blocked forces over these two contact points. The blocked force is expressed in decibel with the reference to the nominal force F_0 = 10^{-6} N in one third octave band.

In Figure 3 the comparison is shown between the averaged blocked force of the standard pipe (#1, solid lines) and that of the straight pipe (#2, dashed lines), on the underground floor, with four volume flow rates. In contrast to the straight pipe, of which excitation sources are originated by the water inlet and the water flow itself, the standard pipe includes three extra excitation sources: two tees and the basement bend. The blocked force of the standard pipe (solid lines) is at most 10 dB higher than that of the straight pipe (dotted lines). The difference varies with the flow rate and frequency, but in general is more prominent at the low flow rate and low frequency. For all cases, the blocked force keeps decreasing with minor oscillations as frequency rises, and the eight lines are getting close to each other above 1 kHz.

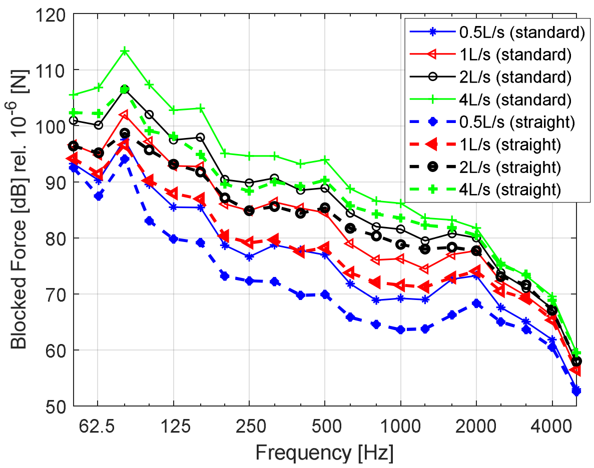

Figure 3: The averaged blocked force of the standard pipe (#1, solid lines) and the straight pipe (#2, dashed lines) measured on the underground floor with the volume flow rates of 0.5 L/s (blue), 1.0 L/s (red), 2.0 L/s (black), and 4 L/s (green).

When the blocked force is plotted as a continuous line in frequency domain as in Figure 3, it is not easy to compare two cases, because they are often close to each other. To highlight the effect of the single excitation sources, the difference of the blocked forces is used between two configurations:

$$\Delta L_{Fb,eq} = L_{A+B} - L_A$$

where L_A denotes the reference case, i.e., the blocked force of the straight pipe arrangement (#2) with the primary excitation sources. L_{A+B} is the force under the primary and an extra source. It must be noted that the positive difference between two cases does not imply that the extra excitation source is the strongest excitation source. As the blocked force is expressed in terms of RMS values in decibels, if L_A is equal to L_B, the sum is 3 dB bigger than L_A. The difference indicates the maximum achievable reduction by completely eliminating the extra excitation source from the system.

Effect of the Bend

Figure 4 shows the difference between $L_{Fb,eq}$ of the straight pipe (#2) and that of the straight pipe with the basement bend (#5) measured in the ground (top plot) and in the underground floors (bottom plot). In each figure, four volume flow rates are plotted. When the colour approaches red, the excitation due to the basement bend more dominates the dynamic response of the pipe, while dark green colour indicates that the effect of the basement bend is negligible.

In both plots, the colour approaches dark green above 1 kHz. It clearly indicates that the basement bend does not affect the transmitted structure borne noise above 1 kHz. Below 1 kHz, the effect of the basement bend increases with the flow rate. The peak frequency of the excitation due to the basement bend is located around 400 Hz. The effect of the flow rate on the peak frequency is not clearly found in Figure 4. The effect of the basement bend appears more clearly on the underground than on the ground floor. One reason must be a distance from the excitation source: The underground is located just above the basement floor, while the ground floor is located beneath the water inlet. The pipe system is weakly segmented by clamps, which is made of metal with rubber inserts. Due to the impedance discontinuity, part of the incoming bending wave is reflected at the clamp. Therefore, the response of the pipe is more controlled by the closest source.

In the plots, the colour of the boxes doesn't change continuously, either in horizontal or vertical direction. For example, in the underground, at 100 Hz and 4 L/s flow rate the light green box appears in the middle of the red area. There can be a few reasons for that. First of all, the tolerance of the measurements repeatability must be considered. Small deviations are caused by slightly different clamping conditions of the pipe and the assembly of the adjacent pipe components after each installation. The physical setting of the pipe is kept as constant as possible during each assembly process, however, the negative effect on the reproducibility of the measurements is inevitable. Secondary, the structure dynamics of the pipe system is modified by exchanging some components. For example, when the pipe system is truncated above the basement bend as shown in Figure 2, the boundary of the pipe system is less constrained than the pipe system with the basement bend and the connected horizontal section. The clamping of the pipe and the boundary conditions influence the resonance frequency of the system. At low frequencies, where the response of the pipe is expressed by the summation of well-separated modes, the shift of the Eigen-frequency has influence on the pipe response.

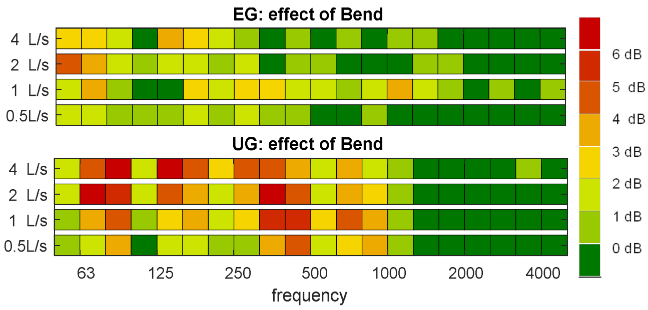

Figure 4: The difference between the averaged blocked force of the straight pipe (#2) and that of the straight pipe with the basement bend (#5), measured on the ground (top plot) and on the underground floors (bottom plot) at different volume flow rates.

Effect of the Tees

Figure 5 and Figure 6 show the difference between $L_{Fb,eq}$ of the straight pipe (#2) and that of the straight pipe with the tee in the ground (#3, Figure 5) and with the tee in the underground (#4, Figure 6), respectively. When the colour approaches red, the excitation due to the tees is more prominent, while dark green colour indicates that the effect of the tees is negligible.

The top plot in Figure 5 and the bottom plot in Figure 6 illustrate the effect of the tee related to the floor, where the tee is installed. Both plots show the similar tendency that (1) the effect of the tee appears above 500 Hz, centred at around 1.5 kHz, and (2) limited to the low flow rate. It does not mean that the water impact on the tee decreases with the flow rate. It simply means that the dominant excitation source changes from tees to the primary source (turbulent flow and the water inlet) as the flow rate rises. This shift of the major source indicates the turbulence grows faster than that. According to [5], the impact force is expressed as a function of the flow velocity raised to the power of 1.2 or slightly higher. As mentioned above, the drainpipe is not filled with water, rather the mixture of water and air. It is known that turbulence is stronger in the mixed flow than in single-phase flow for the same flow rate in a fully filled pipe [6].

Due to the discontinuity of the inner pipe surface at the tee, the water flow on the inner wall is distorted by the tee, and the turbulence of the water increases. Consequently, as shown in the bottom plot in Figure 5, installation of the tee on the ground floor results in the slight increase of the blocked force on the underground floor, though the effect is limited to the low flow rate and low frequency below 1 kHz. On the other hand, the top plot in Figure 6 is in general coloured in green everywhere, this means the tee installed on the underground shows no influence upstream, as the tee induced turbulence affects only downstream due to causality. The location of the tees is another reason. As shown in Figure 1, the tees are located near the bottom of the floor, and thus the effect of the tee is more pronounced on the floor below than the floor above.

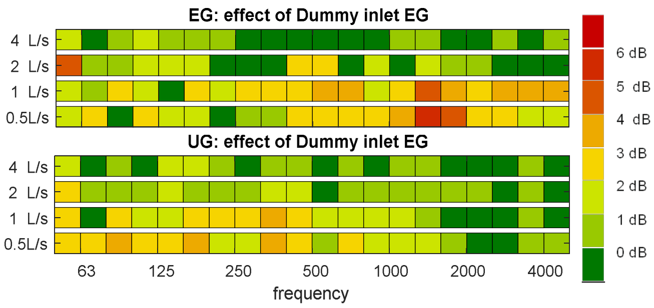

Figure 5: The difference between the averaged blocked force of the straight pipe (#2) and that of the straight pipe with the tee on the ground floor (#3), measured on the ground (top plot) and on the underground floors (bottom plot) at different volume flow rates.

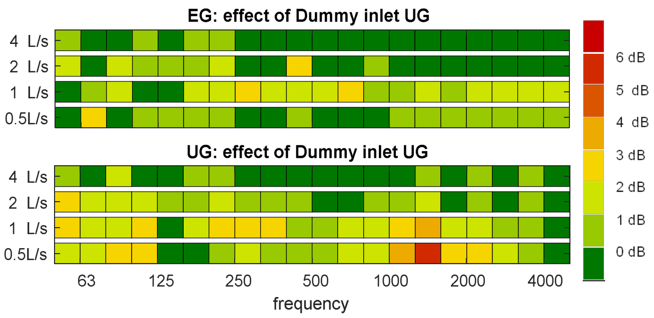

Figure 6: The difference between the averaged blocked force of the straight pipe (#2) and that of the straight pipe with the tee on the underground (#4), measured on the ground (top plot) and on the underground floors (bottom plot) at different volume flow rates.

Conclusions

A total of 20 tests were carried out, 5 different pipe arrangements with four flow rates to investigate the dominant excitation source of the drainpipe with reference to the flow rate and the frequency. The experimental results indicated that (1) the effect of the basement bend rises with the flow rate, but the effect is limited below 1 kHz, (2) the tee has an influence only at low flow rate above 500 Hz on noise at the installed floor, but no influences on the upstream. As a tee distorts the water flow, the turbulence of the flow increases downstream. The effect of this impact force is localized around the related component due to the weak segmentation brought by clamps. At high flow rate and above 1 kHz, the turbulent flow is the main excitation source, and thus cannot be reduced by modifying the pipe arrangement.

For the further investigation of the excitation mechanism in wastewater pipe, it is essential to measure the homogeneous flow velocity and the void fraction between air and water in the pipe, because these parameters are known to influence the turbulence, the impact force, and its peak frequency [5]. As a final step, we aim to express the random excitation of each excitation source by using the Power Spectral Density (PSD) to develop the excitation model, which can be used for any pipe material with the identical inner surface texture and the geometry.

Literature

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