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PREPARATORY WORK TOWARD EXPERIMENTAL ESTIMATION OF WATER EXCITATION TERMS IN WASTEWATER SYSTEMS

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ABSTRACT[*]

Structure-borne sound generated by wastewater pipe systems often dominates noise emissions from sanitary installations in buildings. This paper presents a preparatory investigation aimed at estimation of the water excitation terms by the inverse method. The experimental setup followed EN 14366-1:2023 and the vibration response of the pipe was quantified in terms of the blocked force at the wall fixing points. Noise from wastewater systems is generated by turbulent annular flow and the impact of water at the inlets, tees, and bends. These excitation terms were estimated through a methodical, stepwise approach. First, a customized impact-free inlet was installed to the pipe to eliminate water inlet effects, and thus the annular flow served as the primary excitation source in a straight pipe configuration. Subsequently, the impact of the flow turning elements was evaluated. The numerical model of the drainpipe was then introduced and experimentally verified. Using this model, the inverse method was tested to indirectly identify the applied force acting on the pipe. These presented results serve as the essential basis toward the development of a mathematical model of the stochastic water loads applied to the pipes.

Keywords: *drain pipe, structure-borne noise, EN 14366-1*

1. INTRODUCTION

Wastewater noise is often a problem in adjacent rooms in buildings. When water flows through the pipe, running water induces the pipe vibrations. 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.

Knowledge of flow induced force magnitudes and its predominant frequency is crucial for designing acoustically optimized drainpipes. The drainpipe system is generally not designed to be fully filled with water, to minimize the risk of backflow or overflow. Instead, the flowing water adheres to the inner walls of the pipe, creating a thin film of water with small air bubbles, while air continuously flows through the central region of the pipe. This type of axial two-phase flow pattern is classified as annular flow [2]. The turbulent annular flow causes the unsteady random wall pressure fluctuation. Furthermore, geometrical discontinuities at flow-turning pipe elements such as bends, inlets and tees also have a substantial impact [3]. Finally, the pressure fluctuation on the wall and impact at flow-turning elements causes vibrations on the pipe wall and the system itself.

Simulation of two-phase gas-liquid flow in pipes requires considerable computational efforts due to its great complexity, and thus a large degree is still not characterized by modern-day fluid dynamic models [4]. It is also difficult to experimentally identify the stochastic water excitation terms by transducers. Numerous attempts were made to numerically and experimentally determine the force excitation at the bend and discontinuing element of the pipe [5], however, yet comprehensive analytical model of the water excitation is not available.

On the other hand, the vibration response of the pipe can be conveniently measured [6]. Under these circumstances, indirect methods are preferred, where the input of a system, i.e. water excitation, is reconstructed from its output by inverting the model of a mechanical system. Considering that the water flow is primarily influenced by the internal geometry of the pipe and the friction factor of the inner wall, while the interaction to the pipe vibration is relatively weak, the water excitation term remains unchanged for pipes with comparable geometries and friction factors. Thus, the identified water excitation is applicable to other pipe systems with similar inner geometries and friction

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factors, such as the same pipe configuration but are constructed from new materials like biopolymers or recycled polymers.

A key objective of this study is to establish a methodology for identifying the excitation water force for adapting the excitation model to changes in pipe geometry. This paper presents preparatory work to develop a mathematical model of the stochastic water loads applied to the pipe, using both the experimental responses of the pipe system and a computational dynamical model. First, the experimental setup designed to separate each water excitation term is described, followed by a discussion of the measured results. The numerical model of the drainpipe system is then introduced and experimentally verified. Finally, the inverse method was applied to this numerical model with the measured response to identify the applied point force.

2. PHYSICAL ARRANGEMENT

Figure 1 shows the setup of wastewater systems at the Fraunhofer Institute for Building Physics IBP in Stuttgart. The pipe is made of PP-MD (polypropylene with mineral additives, density 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.

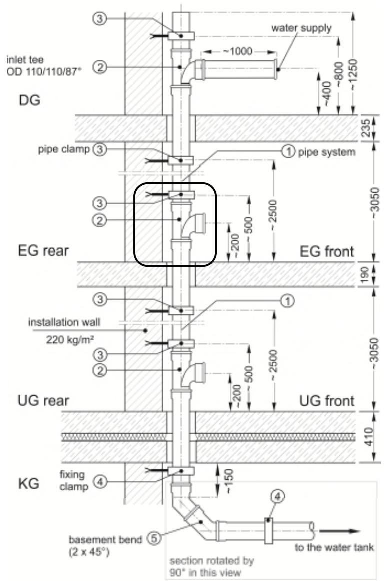

Figure 1: Test facility with the standard wastewater system set-up at Fraunhofer IBP, Stuttgart for measurements according to EN 14366-1:2003 [1].

The structure-borne and air-borne noise measurements are performed according to EN 14366-1:2003 [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 EN 14366-1:2003 [1].

2.1 Blocked Force

Since wastewater systems are connected to the installation wall solely through six clamping points, the vibration response of the pipe was assessed in terms of the forces at these contact points. The contact force between the *i*-th pipe clamp and the installation wall was measured using a force transducer placed between the wall and the clamp (see Fig. 2). Two accelerometers were positioned on the wall near each fixing screw to measure the wall velocity. With this configuration, the power transmitted from the pipe system to the wall via the clamp can be quantified as the real part of the cross-power spectrum of the contact force and the velocity.

The RMS values of the blocked force level at *i*-th clamp position, expressed in dB reference to 10^{-6} N, was indirectly determined using the measured *i*-th installed power, $L_{Ws,i}$, and the pre-determined mobility of the test wall, Y_R [7].

$$L_{Fb,i} \sim L_{Ws,i} - 10\log_{10} \mathrm{Re}\left\{\frac{Y_{R,i}}{Y_0}\right\} \quad (1)$$

where Y_0 = 1 m/sN, the reference value of mobility. The installed power L_{Ws} is expressed in decibels relative to the reference nominal power W_0 = 10^{-12} Nm/s. The blocked force on the installation wall can be used as an input to estimate the structure borne noise in the adjacent rooms [7].

Figure 2. A force transducer and two accelerometers on the installation wall.

2.2 Separation of Excitation Sources

As shown in Fig. 1, the standard pipe system extends four floors. The system consists of the straight pipes with the water inlet in the attic ('DG' in Fig. 1), two tees (closed with a lid) situated on the ground and the underground floors ('EG' and 'UG'), and the bend with 2 x 45-degree angle in the basement ('KG').
The excitation sources of this pipe are separated into the following four components: (1) turbulent water flow on the pipe wall, (2) impact force at the water inlet, (3) waterfall at the tee on EG and UG, and (4) waterfall on the basement bend. It is assumed that the air-borne noise generated by the system doesn't influence vibrations of the pipe. To effectively isolate each excitation source, the pipe setup needs to be modified from the standard arrangement.

2.2.1 Tees and basement bend

To eliminate the effects of the tees, each tee can be replaced with straight cylindrical pipes of the equivalent length. Similarly, the basement bend can be decoupled from the system and replaced by a bend with a larger diameter than that of the pipe system, to ensure no physical contact between the bend and the upper drainpipe. A thin waterproof membrane loosely covers the lower end of the drainpipe system to prevent splashing water falling onto the bend (see Fig. 3).
The flow impacting the disconnected basement bend generates noise, which may be comparable to or exceed the excitation caused by the turbulent water flow. To suppress airborne noise from the bend, the bend is covered by mass-loaded pipe insulation. The laboratory measurements indicated that the vibration caused by the airborne noise from the insulated bend is at least 10 dB lower than that caused by the turbulent annular flow.

Figure 3: The decoupled basement bend covered by mass-loaded pipe insulation with the loose waterproof membrane cover.

2.2.2 Impact-free inlet for laboratory testing

The impact-free inlet (see Fig. 4) was designed for the laboratory tests presented in this paper to eliminate the effects of water hammer caused by the water inlet. This inlet consists of a thin metal pipe with a closed-end short cylinder. The metal pipe is inserted into the cylinder and welded to its bottom cap. Near the welded edge, three rectangular openings are formed, each measuring 10 mm by 20 mm with rounded corners. The total opening area exceeds 600 mm², which is larger than the inner cross-sectional area of the metal pipe (560 mm²), ensuring smooth water flow from the metal pipe to the cylinder. Finally, the cylinder with the metal pipe is inserted into the drainpipe to a depth of 325 mm from the top and is carefully positioned at the center of the drainpipe. This impact free inlet was first fixed to the 20 mm wooded board, and the board was fixed to a separate wall section via 25 mm of elastomeric material, made of polyurethane foam. The inlet has no direct contact to the main drainpipe to prevent the structure borne excitation from the flow conditioner to the drainpipe.

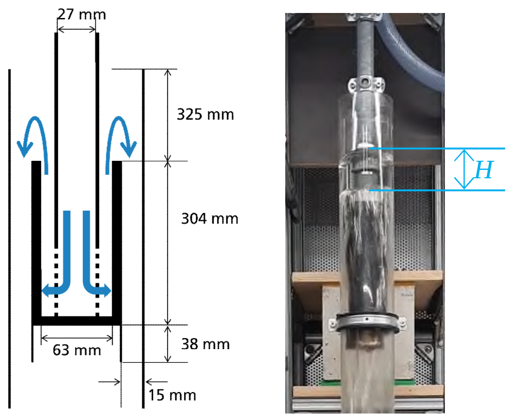

Figure 4: (a) The design of the impact-free inlet, (b) photo the impact-free inlet during operation.

Initially, water flows through the metal pipe and then flows into the cylinder through the side openings. In the cylinder, water runs upward, and then spills over from the upper opening of the cylinder. Finally, water moves into the gap between drainpipe and the cylinder. To prevent water from flowing to the back side of the bottom cap and dripping off, the outer wall of the cylinder is vertically extended by 38 mm using a thin metal sheet.
The flow conditioner begins functioning at a flow rate of 0.7 l/s and operates stably above 1.0 l/s. At flow rates below 0.7 l/s, water tends to flow along the cylinder wall rather than the drainpipe wall. Additionally, due to the constraints of the inner pipe's size, the maximum achievable flow rate

is limited to 3.0 l/s. Therefore, in this study, the water flow rates examined are 1.0 l/s, 1.5 l/s, 2.0 l/s, and 3.0 l/s, while the common flow rates of 0.5 l/s and 4.0 l/s [1] were not included in the measurements.

2.3 Water Velocity

When the volume flow rate exceeds approximately 1.0 l/s, the upward water in the cylinder flows beyond the top edge of the cylinder and fills the drainpipe above. The surface of the filled water is softly rippled due to the upward water flow underneath, but the height remains relatively constant over time. Table 1 summarizes the measured filled heights from the upper edge of the cylinder, shown as H in Fig. 4 (b). Starting from this upper surface, the flow continues to accelerate due to gravity until it reaches a terminal point, where the gravitational force is equal to the wall shear stress. The velocity at this point is referred to as the terminal velocity. According to [8], the terminal velocity of the annular flow, v_t, and the vertical distance required to achieve terminal conditions, d_t, are respectively expressed by the following formulas:

$$v_t = \left(\frac{1}{n^2}\frac{1}{\pi^{\frac{4}{3}}}\right)^{0.3}\left(\frac{Q_w}{D}\right)^{0.4} \tag{2}$$

$$d_t = \frac{1.42}{g}v_t^2 \tag{3}$$

where Q_w is the volume flow rate, D is the inner diameter of the drainpipe, and g = 9.81 m/s^2. The coefficient n is related to the surface roughness suggested by Manning and was set to 0.007 in this study [8]. The predicted values for each flow rate are summarized in Table 1.

Table 1. The terminal velocity v_t, the terminal distance d_t, and the filled height H with reference to the flow rate.

Flow rate	v_t [m/s]	d_t [m]	H [m]
1.0 l/s	3.89	2.2	0.02
1.5 l/s	4.31	2.7	0.04
2.0 l/s	4.63	3.1	0.075
3.0 l/s	5.12	3.8	0.13

The terminal point, at which the flow reaches terminal velocity, should be measured from the upper surface of the filled water, where the vertical velocity of the water is zero. As the filled water prevents air from being drawn in or released from the pipe, the water in the narrow gap between the cylinder and the drainpipe flows without air, at least partly. In this region, the acceleration of the flow is zero, i.e., constant velocity due to mass conservation law. Therefore, total the length of the cylinder with the extended cover, 342 mm, should be added to the distance calculated by Eqn. (3). The terminal point is explicitly shown in the Fig. 5 for each flow rate. These heights are valid for the pipe system using the impact free inlet, but not for the standard pipe setting.

It must be noted that terminal conditions are strongly influenced by the surface roughness of the pipe, n, which depends not only on the material, but also on manufacturing process and the environmental factors. The applied value n = 0.007 is appropriate for the very smooth surface. When the actual surface roughness is higher than the applied value in this paper, the terminal velocity decreases and thus the flow reaches the terminal condition at higher position than drawn in the Fig. 5. Therefore, the presented values in Table 1 should be regarded as the upper limit rather than definitive values. Nevertheless, this estimation indicates that the flow velocity is rather constant in the underground section, while the flow continues to accelerate on the ground floor.

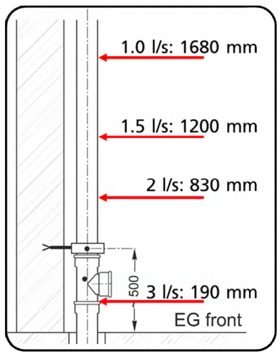

Figure 5: The magnified view of Fig. 1 around the ground floor with the position reaching terminal velocity for each flow rate.

3. EXPERIMENTS

Three different pipe arrangements were tested with four different flow rates. The 1st configuration is the standard model (shown in Fig. 1) with all flow turning elements, while the straight drainpipe, the 2nd configuration, is composed of the straight cylindrical components only. The water runs into the pipe from the impact free inlet, and the bend is disconnected. Under this configuration, the straight pipe is excited only by the annular turbulent flow. The 3rd model is composed of the straight pipe with a tee on the ground floor.

3.1 Straight Pipe

Figure 6 shows the blocked force of the straight pipe at four clamp positions on EG and UG with the flow rate of 2.0 l/s, which empirically exhibited the highest repeatability.

For all cases, the blocked force keeps decreasing with minor oscillations as frequency rises. In the absence of additional pipe components, the blocked force values at all four clamp positions were comparable. Particularly, the forces measured at clamps on the underground floor (green and black curves) overlaps quite well across the entire frequency range. The red curve shows slightly lower values than these two overlapping curves, while the blue curve was again slightly below the red curve. It comes from the fact that the flow reached the terminal velocity near the ground level of the ground floor. According to Fig. 1, the 2.0 l/s flow reaches the terminal velocity at around 300 mm above the lower clamp position on the ground floor. Therefore, the speed of the annular flow in the pipe was constant over the vertical direction in the underground floor, while the flow still accelerates in the upper section of the ground floor.
The sharp drop of the red curve around 2 kHz may come from the weak contact of the accelerometer on the wall with the surface coating. It is expected that the red line remains between the blue and black lines.

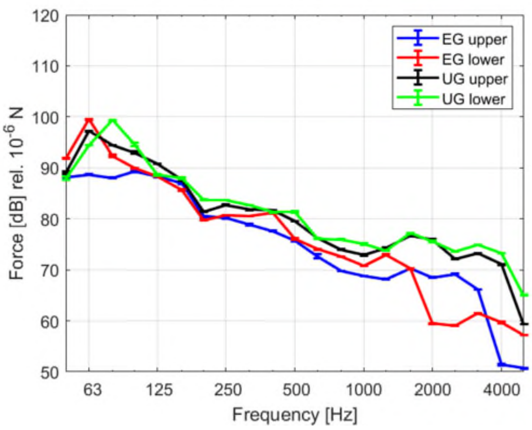

Figure 6: The blocked force of the straight pipe (#2) on four clamp positions on EG and UG with the flow rates of 2.0 l/s.

3.2 Maximum Achievable Reduction

Four plots in Fig. 7 visualizes the difference between the blocked force of the standard pipe (#1) and that of the straight pipe (#2) at four clamp positions. The difference of the blocked forces reaches even above 15 dB at every position, because the standard pipe has additional excitation sources to the straight pipe, such as an inlet, tees and a bend. The difference highlights the potential for maximum achievable reduction by optimizing the geometry of these flow-turning elements, to the point where the excitation forces are theoretically reduced to zero. Although this is not feasible, Fig. 7 represents the upper limit of possible reduction.
The difference varies with the flow rate and frequency, but in general is more prominent at the low flow rate and low frequency. Above 2 kHz, the difference is diminishing. It indicates that the annular flow dominates the vibration of the pipe, or at least the annular flow is comparable with other excitation sources.

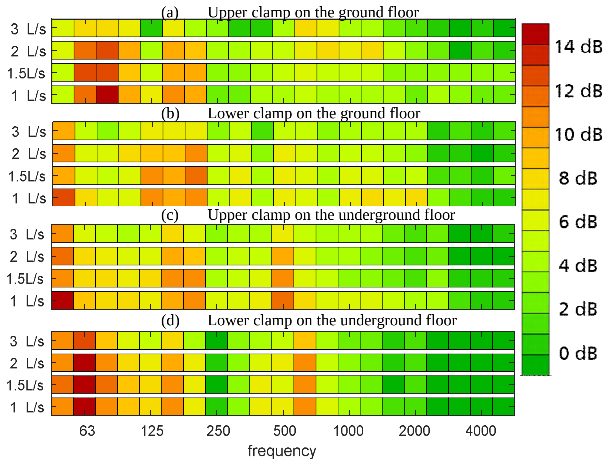

Figure 7: The difference between the blocked force of the standard pipe (#1) and that of the straight pipe (#2), measured on the upper (a, c) and lower (b, d) clamps on the EG (a, b) and UG (c, d) with different volume flow rates.

3.3 Effect of the Tee

Figure 8 shows the difference between the blocked force of the straight pipe with (#3) and without (#2) the tee on the ground floor. The effect is most prominent in plot (b): the blocked force at the clamp located only 300 mm above the tee. The peak appears around 1.5 kHz, and the effect is stronger with low flow rate. The effect also clearly visible in Plot (c): the adjacent clamp located approximately 1000 mm away from the tee in the downstream. The affected frequency range becomes broader, particularly towards lower frequency. It indicates that the effect of the tee is not only the local impact, but also the flow distortion toward downstream. When water flows through the pipes with the tee, the tee is partially filled with water, and thus the water movement around the circular perimeter of the tee is not uniform. Finally, the tee causes the flow disruption.
On the other hand, the tee effect is only fairly visible at the first clamp, which is located approximately 2 m above the tee. The effect is similar to that of the nearest clamp, but much lower amplitude, because the impact propagates

along the pipe with energy loss. On the furthest clamp in plot (d), the effect of the impact is merely visible. Only broadband effect is slightly visible at the lowest flow rate of 1 l/s. It indicates that the length necessary for the flow to stabilize again after the tee disruption varies with the flow rate. It probably comes the different film layer thickness. Theoretically, the layer thickness at the terminal velocity depends on the flow rate [8] and reaches 1 mm (1 l/s) to 2 mm (3 l/s). With low flow rate, this thin film does not fully coat the entire inner surface of the pipe; instead, it only partially covers it. When the water layer is thicker, the effect of the disruption can be quickly recovered.

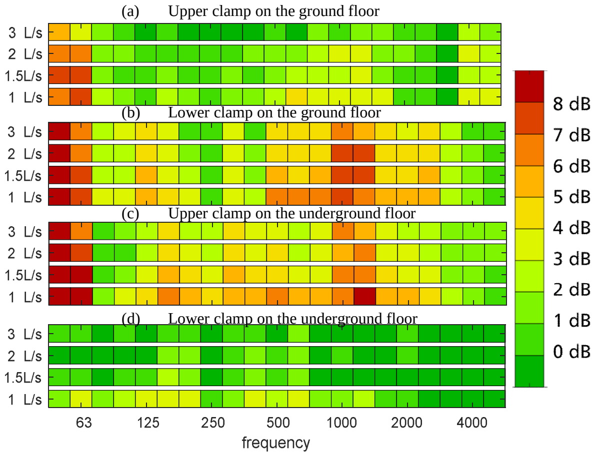

Figure 8: The difference between the blocked force of the straight pipe (#2) and that of the straight pipe with the tee on EG (#3) in dB, measured on the upper (a, c) and lower (b, d) clamps on the EG (a, b) and UG (c, d) with different volume flow rates.

4. NUMERICAL MODEL

In addition to the experiments, a detailed numerical model of a drainpipe was built by the commercial Finite Element (FE) software COMSOL (version 6.3) to simulate vibration due to structural excitation. However, direct measurement or CFD simulation of the random dynamic loads generated by the turbulent flow within the pipe is very challenging [4]. Therefore, it is necessary to indirectly identify the random dynamic loads from the measured blocked force with the aid of the numerical model.

The identification of stochastic loads applied to dynamical systems using uncertain computational models with experimental data is a classic but still active topic [9]. This problem is challenging, because the inverse method often amplifies both numerical model uncertainties and experimental data uncertainties, resulting in inaccurate solutions. Therefore, numerous papers have been published focused on robust identification methods to suppress the impact of uncertainties. Nevertheless, the final reconstructed load heavily relies on the quality of the numerical model. A FE approach is a promising solution to construct a reliable detailed model of the dynamic system. However, it is computationally extremely complex to model all the details of the drainpipe. Furthermore, even a finely constructed numerical model cannot reproduce exactly the real behavior of a structure due to limitations of the model itself.

Therefore, the following simplifications were applied to the model to keep a balance between simulation accuracy and computational efficiency: (1) The pipe structure is modelled by shell elements, while the screw is modelled by solid elements. (2) The pipe is fixed to the impervious rigid wall. Although the mobility of the installation wall affects the measured results particularly at low frequency, they are essentially not related to the acoustic performance of the drainpipe. (3) Air-borne noise, both the noise in the pipe and the radiated sound from the pipe the room, is ignored. (4) the pipe clamp with the rubber inlay is modelled by the single layer shell with the equivalent damping of two layers.

4.1 Experimental Verification

The developed FE model should be verified with reference to the experimental data obtained from the actual structure to assess its predictive capability. Instead of stochastic water excitation, the deterministic point force generated by a small inertia shaker was applied to the pipe. The shaker was attached to the pipe on 300 mm above the ground on the 1st floor (‘DG’ in Fig. 1) via the 2 mm thick steel clamp and was oriented normal to the wall (see Fig. 9). The shaker was driven by the band limited pink noise, and the exerted force was measured by the force transducer attached between the shaker and the pipe clamp.

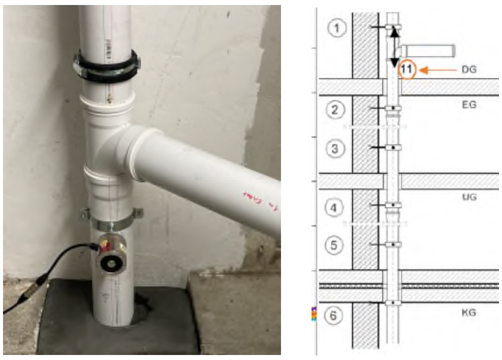

Figure 9: The configuration of the pipe with the attached shaker.

The measured exerted force by the shaker was used as input force in the FE model. The material parameters of the pipe are summarized in Table 2, while the geometrical parameters are visualized in Fig. 1. The Young's modulus of elesticity and the loss factor of the pipe were experimentally identified by the modal analysis using a 2 m long pipe piece. The vibrations of the pipe were simulated in 1/24th octave band frequency resolution between 44 Hz and 1.4 kHz, which are respectively the lower and the upper frequency limits of the octave band, centered at 62.5 Hz and 1 kHz.

Figure 10 compares the measured (black) and simulated (red) blocked forces at the lower clamp on the ground floor. Although some discrepancies are observed, particularly at low frequencies below 100 Hz, the overall agreement is substantial in terms of both amplitude and peak frequencies. The narrowband spectra show that most peaks and dips are accurately represented by the simulation, although minor shifts in peak frequencies are noticeable.

Table 2. Material parameters of the drainpipe systems used in the FE model

Parameter	Pipe	Clamp
E-modulus	3.92 GPa	200 GPa
Poisson ratio	0.3	0.3
Density	1700 kg/m^3	7850 kg/m^3
Loss factor	0.055	0.1

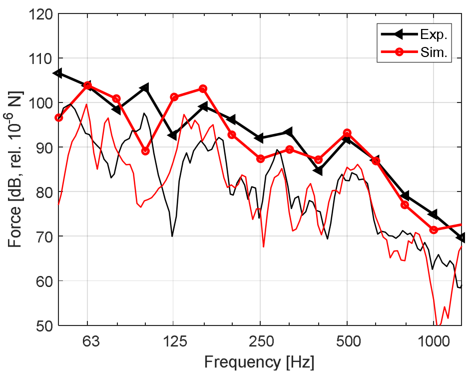

Figure 10: Comparison of the measured (black) and the simulated (red) blocked force at the lower clamp on EG.

4.2 Inverse Determination of the Point Force

As the simplest case study for the verification of the inverse method, the pipe system in the previous section is considered. The applied point force is identified through an inverse analysis using the FE model and the measured blocked forces. The accuracy of the identified primary force can be readily assessed by comparing it to the measured primary force.

The blocked force at i-th clamp position, f_{bl}^i, can be expressed as follows:

$$f_{bl}^{i}(\omega) = H^{i}(\omega) f_{p}(\omega) \quad (4)$$

where H^i is the transfer function between the point force and the i-th blocked force, and f_p is the point excitation force. The transfer functions of the FE model can be easily obtained from the simulation results with trivial primary force, such as, f_p = 1 N. Solving Eqn. (4) under the given boundary condition, e.g. the measured blocked force, leads to the unknown point force, f_p. The Least Square Method (LSM) is used to compute the frequency-dependent point force, f_p, by minimizing the sum of the differences between the measured and simulated blocked forces.

$$\epsilon = \sum_{i=1}^{6} \left| f_{bl,m}^{i}(\omega) - H_{s}^{i}(\omega) f_{p}(\omega) \right|^{2} \quad (5)$$

where the subscript m and s denotes "measured" and "simulated", respectively.

This is a straightforward approach without any advanced methods to enhance its robustness against uncertainties. As shown in Fig. 11, the predicted point force (blue curve) doesn't align well with the measured applied force, though the simulated values fluctuate around the measured values. Both numerical model uncertainties in H^i and experimental data uncertainties of $f_{bl,m}$, result in inaccurate prediction of the primary force.

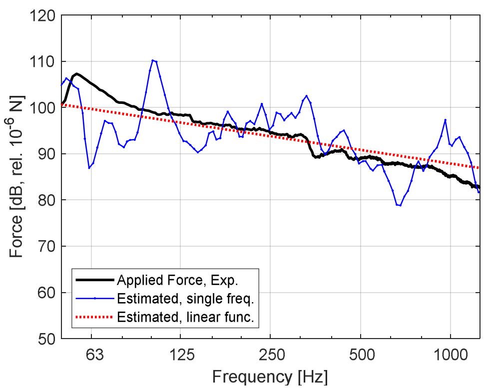

Figure 11: Comparison of the measured excitation force by the shaker (black), and the estimated point force by the direct inverse method without (blue with dots) and with the predefined excitation function (red dotted).

To improve the prediction accuracy, additional constraints must be imposed on the model. Assuming that the primary force is a linear function in double logarithmic scale,

$$f_{p}(\omega) = b \cdot \omega^{a} \quad (6)$$

the coefficient *a* and *b* can be estimated by the LMS method. The estimated point force was plotted by the red dotted line in Fig. 11. The agreement was significantly improved. The gradient of the predicted force in double logarithmic scale was -2.96 dB per octave, which is very similar to the pink noise characteristics. This case study proves that the inverse method can predict the input excitation terms using the FE model of the drainpipe and the measured blocked forces, but additional constraints are crucial for reliable results.

5. CONCLUSIONS

This paper presented preparatory work to develop a mathematical model of the stochastic water loads applied to the pipes.

Through experiments, the impact of each excitation source was separately investigated, and their contributions were quantified. The excitation terms generated by water flow within the drainpipe was separated by using the impact-free inlet as well as the decoupled or replaced flow turning elements. The analysis highlighted the significance of annular flow at high frequencies, while flow turning elements have significant influence at low frequency. Their effect is more prominent with low flow rates.

The three-dimensional finite element (FE) model of the drainpipe was developed and demonstrated a good agreement with measured blocked forces. Using this FE model, the inverse method was tested to identify the point force acting on the pipe. By incorporating additional constraints, the primary force was predicted with high accuracy. This approach emphasizes the importance of additional constraints to improve the accuracy of the results. Although the point force itself is considered deterministic rather than stochastic, this study verified the applicability of the inverse method with the measured blocked force and the developed FE model.

Future work will focus on the development of a mathematical model of the stochastic water loads applied to the pipe using both experimental responses of the pipe system and a computational dynamical model of it. The water excitation and structural response are regarded as a stochastic process and should be described in the form of a power spectrum density (PSD). To derive appropriate additional conditions for the inverse method, it is essential to measure the homogeneous flow velocity, because these parameters are known to influence the turbulence, the impact force, and its peak frequency [2]. Additional measurements are planned to assess the effect of other flow turning elements.

6. ACKNOWLEDGMENTS

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