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WASTEWATER PIPES AS STRUCTURE-BORNE SOUND SOURCES: LABORATORY MEASUREMENTS AND FINITE ELEMENT ANALYSIS

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ABSTRACT

The noise emitted by waste water pipes is, in most cases, generated by structure-borne sound transmission. The water flowing through the pipe causes a vibration of the pipe system that is transmitted to the installation wall through pipe clamps. Laboratory measurements and finite-element simulations of a waste water pipe, excited by an electrodynamic shaker (to simplify the real excitation by water), were used to characterize the pipe as a structure-borne sound source by its blocked force, free velocity and mobility. The characterization is carried out 1.) on the freely suspended pipe and 2.) in-situ with the pipe installed on a reception plate according to EN 15657 [2]. The overall aim of this study is to provide source data for waste water pipes that can be used for the prediction of the sound transmission in buildings using EN 12354-5 [3] with respect to the recently revised EN 14366-1 that is currently being used for the characterization of wastewater pipes.

Keywords: *structure-borne sound transmission, pipe noise, finite element analysis*

1. INTRODUCTION

The noise emitted by wastewater pipes is a common problem that affects the quality of buildings. This noise is often caused by structure-borne sound transmission, where the vibration of the pipe system, induced by the water flow, is transmitted to the installation wall through pipe clamps. In order to predict the sound transmission in buildings, it is necessary to have accurate source data for wastewater pipes.

2. MEASUREMENT METHODS

A three meters long wastewater pipe made of polypropylene is characterized as an active structure-borne sound source. The connection to the receiving structure is made via two pipe clamps with a rubber inlay as an isolation measure. For excitation of the pipe, an electrodynamic inertial shaker is connected to the pipe at a distance of 10 cm from the pipe end and operated with white noise.

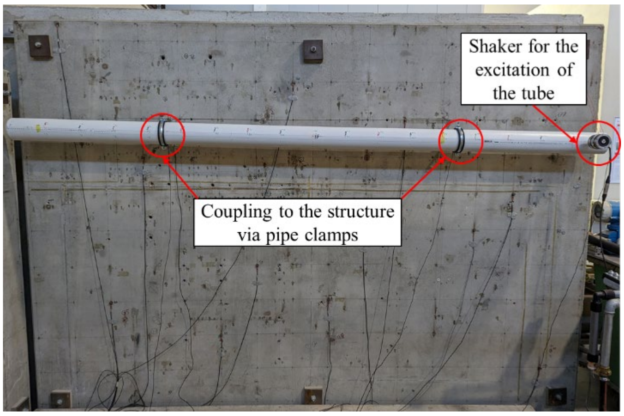

Figure 1. Wastewater pipe mounted on the reception plate with pipe clamps and an inertial shaker for excitation of the pipe

When predicting the structure-borne sound transmission according to DIN EN 12354-5 [3], the power transmitted into the receiving structure W is required. In the general case, this can be calculated from the free velocity v_{sf}, the mobility of the source Y_S and the mobility of the receiving structure Y_R using the following formula [4,5]:

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$$W = \frac{1}{2} \frac{|v_{sf}|^2}{|Y_S + Y_R|^2} Re\{Y_R\} \qquad (1)$$

The mobility of the source structure has to be determined at the contact points on the threaded rod of the pipe clamp, as shown in Fig. 2 For this purpose, an aluminium indenter was screwed onto the threaded rod in order to be able to mount the accelerometers.

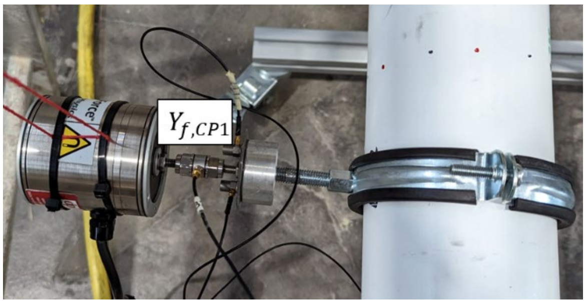

Figure 2. Mobility measurement at contact point CP1 of the pipe with the receiving structure.

Since in this case the mobility of the receiving structure is significantly lower than that of the source, see Fig. 3 and thus $Y_S \gg Y_R$ holds, (1) can be simplified to:

$$W = \frac{1}{2} |F_b|^2 Re\{Y_R\} \qquad (2)$$

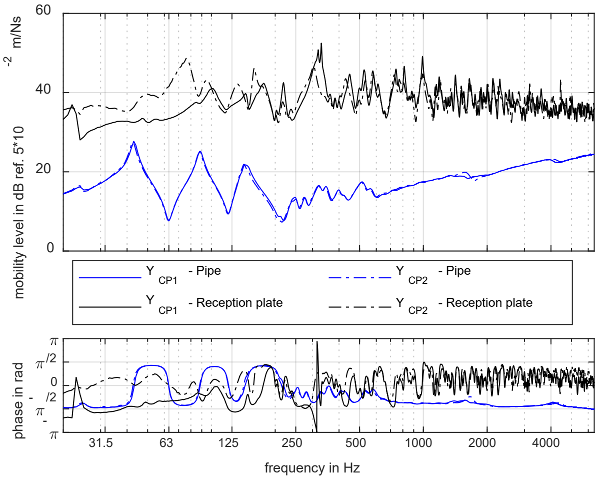

Figure 3. Mobility at the contact points of the pipe and the reception plate

Therefore, with the blocked force F_b, the source (wastewater pipe + pipe clamps + shaker) can completely and independently from the receiver be characterized as a structure-borne sound source in heavy buildings. For the case of freshwater pipes, it has been shown that with the blocked force a prediction according to DIN EN 12354-5 is possible [6]. In this paper, the active pipe is characterized by means of three measurement methods. According to DIN EN 15657 [2], the pipe can be characterized mounted on the receiver plate, see Fig. 1, or by measuring the free velocity and mobility of the contact points of the freely suspended pipe, see Fig. 4 (right). In addition, the force transmitted into the receiving plate was measured directly at both contact points using force sensors mounted between the pipe clamps and the receiving structure as a reference. The installation situation of the force sensors is shown in the following figure.

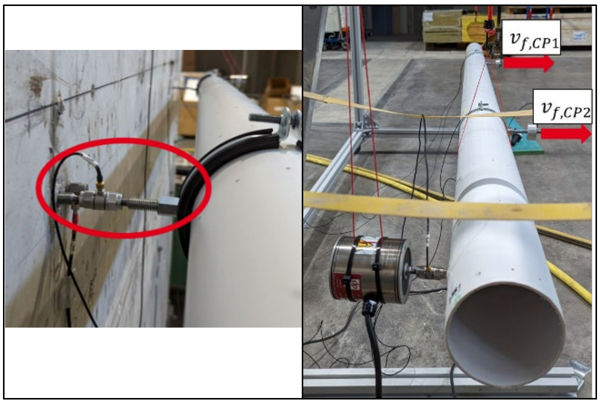

Figure 4. Measurement methods for determining the blocked force – Left: Force sensor between pipe clamp and receiving structure; Right: Measurement of the free velocity at the contact points of the freely suspended pipe.

The reception plate method is based on measuring the mean velocity $\bar{v}$ on the reception plate at steady state operation of the source. Using the loss factor η determined from the structure-borne reverberation time and the mass m of the plate, the power transmitted into the reception plate W_{rec} can be determined from [2]:

$$W_{rec} = \omega \cdot m \cdot \bar{\tilde{v}}^2 \cdot \eta \qquad (3)$$

The velocities at the 12 measurement positions on the reception plate and the mean value are shown in Fig. 5.

With the equivalent point mobility $\bar{Y}_{rec}$ of the reception plate averaged over the contact points CP1 and CP2, the single equivalent blocked force $\tilde{F}_b$ can be determined from:

$$\tilde{F}_b^2 = \frac{W_{rec}}{Re(\bar{Y}_{rec})} \tag{4}$$

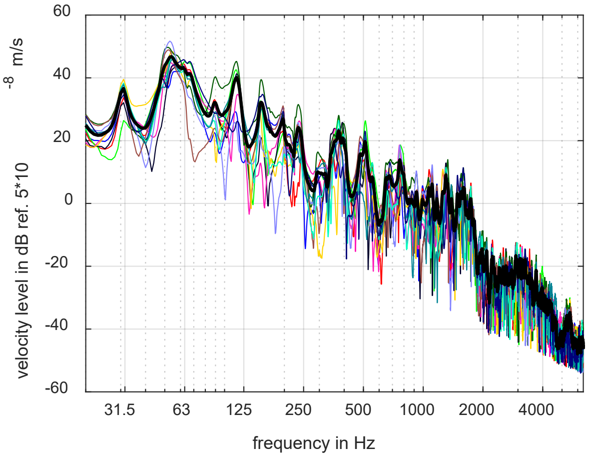

Figure 5. Velocities on the reception plate as mean value (black curve) and at each measurement position (colored curves)

To determine the blocked force of the freely suspended pipe, the free velocity vector v_{sf}, see Fig. 6, and the mobility matrix Y, see Fig. 3 are measured. From this, the blocked force F_b at the two contact points can be calculated according to equation (5)

$$\begin{bmatrix} F_{b,CP1} \\ F_{b,CP2} \end{bmatrix} = \begin{bmatrix} v_{sf,CP1} \\ v_{sf,CP2} \end{bmatrix} \cdot \begin{bmatrix} Y_{f,CP1} & Y_{f,CP1-CP2} \\ Y_{f,CP2-CP1} & Y_{f,CP2} \end{bmatrix}^{-1} \tag{5}$$

Since the receiving plate method yields only one single equivalent blocked force, the forces of the two contact points are summed up for comparison with the other two methods:

$$\tilde{F}_{b,ges}^2 = \tilde{F}_{b,CP1}^2 + \tilde{F}_{b,CP2}^2 \tag{6}$$

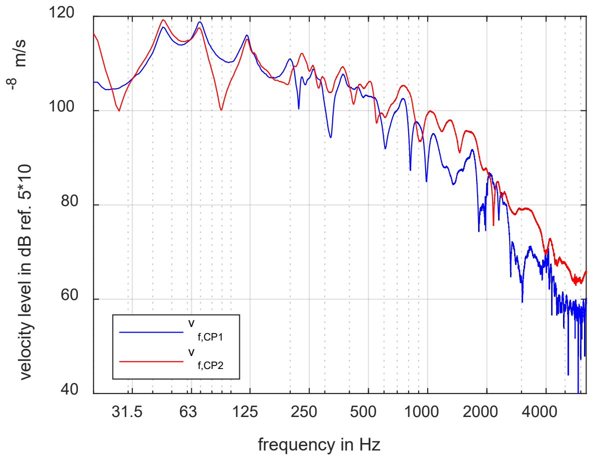

Figure 6. Free velocities measured at the contact points of the freely suspended pipe

3. MEASUREMENT RESULTS

After carrying out the measurements and evaluating them according to the three methods described, the results shown below are obtained for the blocked force. The measurements and evaluations were performed in narrow bands and then converted to third-octave values

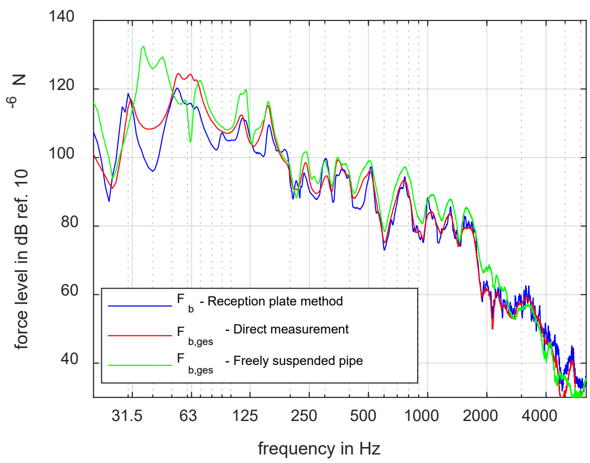

Figure 7. Velocities on the reception plate as mean value (black curve) and at each measurement position (colored curves)

The maxima of the blocked force are determined by the Eigenmodes of the pipe [1]. The force tends to decrease with frequency. The measurement on the freely suspended pipe results in a slightly higher force than for the other two methods. Overall, the agreement between the three methods is good.

4. FINITE ELEMENT SIMULATION

To reproduce the measurement setup in the FE simulation, the geometry must first be created as a CAD model. The pipe clamp is modeled in a simplified way by rotating the profile of the pipe clamp around the pipe. The CAD model is shown in Fig. 8

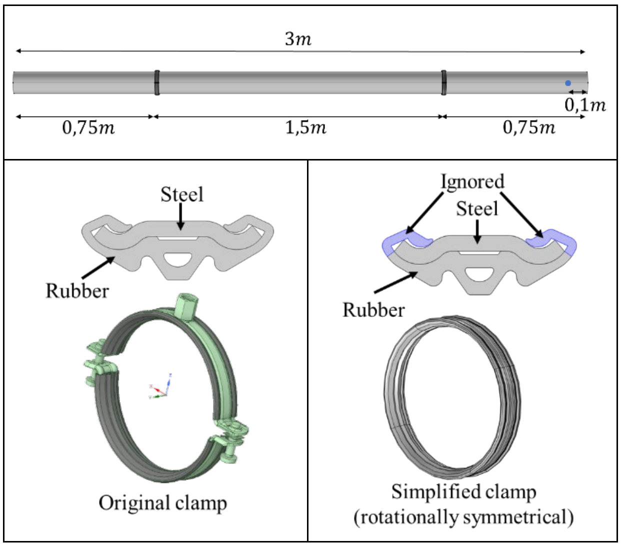

Figure 8. CAD model of the wastewater pipe and simplification of the pipe clamp in the FE simulation.

For the finite element modeling, the material data of the pipe and the pipe clamp must be assigned to the respective components. The boundary condition is assumed to be a composite contact between the pipe clamp and the pipe. The supports of the pipe clamp are defined as point supports and the force of the shaker is assumed to be a harmonic point load.

After the discretization of the geometry and definition of the study type, the calculation can be performed. The reaction forces of the position are then evaluated; these correspond to the blocked force.

Compared to the characterization by measurement, the simulation provides not only the blocked forces but also the vibration at all discrete points on the pipe and the pipe clamp. This can explain the fact why contact point 2, which is closer to the excitation position, dominates the frequency response at high frequency. Figure 9 shows the reaction forces of the two contact points (red and blue curves) and the sum of the two (black curve).

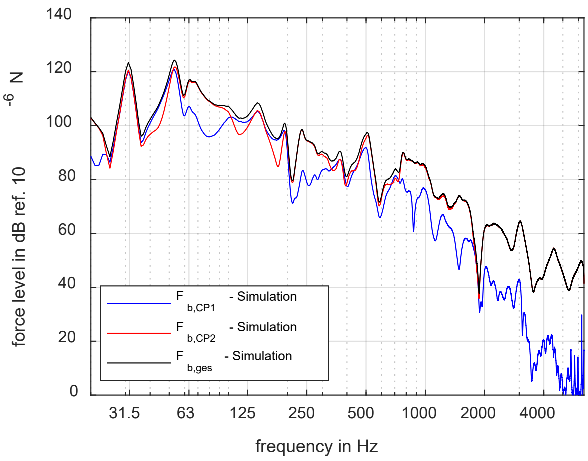

Figure 1. Force response of the contact points and their sum

The vibration on the pipe at high-frequencies decreases with increasing distance from the point of excitation due to the propagation damping. As an example, the vibration shape at 3660 Hertz is shown in the following figure:

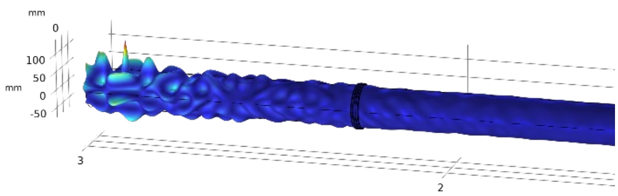

Figure 2. Vibration shape of the waste water pipe at 3660 Hz

5. COMPARISON OF MEASUREMENT & SIMULATION

In order to evaluate the quality of the simulation, the forces of the individual contact points are first compared between direct measurement and simulation, see Fig. 11. The single equivalent blocked force according to formula (6) is then compared.

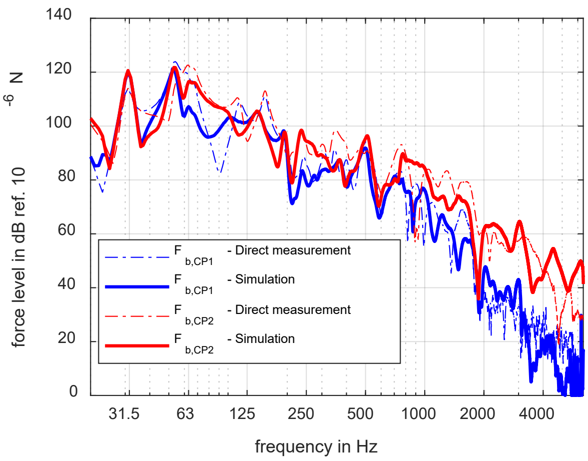

Figure 3. Comparison of the blocked force of each contact point for direct measurement (dashed, thin line) and results of the FE simulation (thick line)

As can be seen that there are deviations between the directly measured and the calculated blocked forces, for example the maxima do not always match. Overall, however, the simulation is able to predict the frequency spectrum of the blocked force well. Thus, the results of the FE simulation are already good. Improvements can still be made in the model, for example a more accurate modeling of the pipe clamp, in which the rubber insert is prestressed and compressed by the assembly as in the real mounting condition.

In the following, the results of the single equivalent blocked force for the measurement methods are compared with the FE simulation in Fig. 12. This shows that the simulation results fit well with the results of the experimental characterization. In most cases, the simulation result lies between the results of the experimental methods.

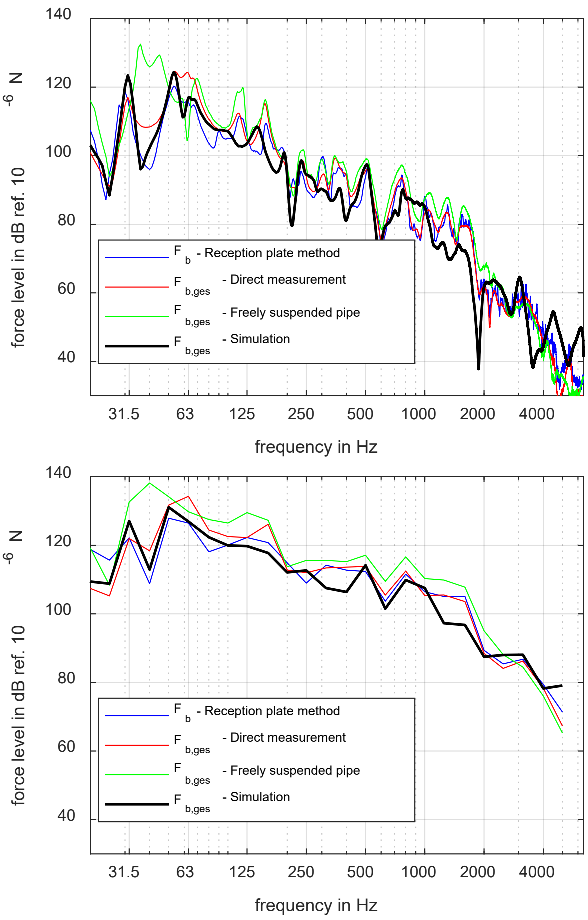

Figure 4. Comparison of single equivalent blocked force between experimental and computational characterization

6. CONCLUSION

A wastewater pipe excited by a shaker was characterized as an active source of structure-borne sound via the blocked force. The experimental characterization was carried out with the receiving plate method, the measurement of free velocity and mobility and via the direct measurement of the injected force. All methods used show good agreement and are therefore suitable.

In addition, the active wastewater pipe was modeled in an FE simulation and computationally characterized by determining the same parameters as in the measurement. The agreement of measurements and simulations is satisfactory. It has thus been shown that the active wastewater pipe can also be characterized using the finite element method. In the future, this will allow further investigations using the FE model, for example parameter studies with different materials or modified geometries, without having to carry out time-consuming measurements.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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