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S.E.A.-MODELING OF STRUCTURE-BORNE SOUND TRANSMISSION VIA WASTEWATER PIPE SYSTEMS TO BUILDING STRUCTURES AND ROOMS

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ABSTRACT
In this research a model based on Statistical Energy Analysis (SEA) is being developed to describe the sound transmission from pipe systems to building structures and rooms. The mode number of the excited wave types in these elements is relatively high in the 1/3-octave bands, at least in the mid and high frequency range. Therefore the SEA-approach is useful to describe the sound transmission in this frequency range. To collect loss factor data for the model a measurement method based on the Power Injection Method (PIM) has been developed. This method has been evaluated for a system consisting of a wastewater pipe and a building structure, connected with each other by a clamp. The measurements show good repeatability and reproducibility results. To improve the reciprocity more research has to be done.

1 - INTRODUCTION

In residential and other buildings many people are annoyed by noise caused by sanitary installations, including the sound transmission via wastewater pipe systems. In order to avoid annoyance limits to the maximum allowable sound level in rooms and some design tools are set in several building regulations. However, the maximum allowable sound level in a room is often exceeded. To avoid these problems and in order to decide about measures during the design stage of a building, it is necessary to predict the sound level based on the design of both building and installation.
In this research a model based on Statistical Energy Analysis (SEA) is being developed to describe the sound transmission from pipe systems to building structures and rooms. To collect loss factor data for several system elements a method for measuring loss factors has been developed based on the Power Injection Method (PIM). This paper gives a description of the model. Further, the measurement method and some measurement results are discussed.

2 - MODELING OF SOUND TRANSMISSION VIA PIPE SYSTEMS

The problem has been described by a system, consisting of two subsystems, i.e. the pipe and the building structure, connected with each other by clamps. The separate wave types (modes) inside the subsystems have been called sub-subsystems. Due to its small dimensions a clamp is not a subsystem itself, because no separate wave behavior exists inside this element. A detailed SEA-model with all wave types and their main vibration directions is given in figure 1. The bold printed paths in this figure determine the sound radiation by the pipe and the building structure to a room.
Due to the turbulent water flow, discontinuities (represented by the power input P_{in} in figure 1) and the relatively large pipe dimensions in especially toilet wastewater systems several wave types are excited in the pipe system. Firstly, in the pipe fluid acoustic modes (plane waves with circumferential mode number n=0) exist. Secondly, in the pipe wall longitudinal (n=0) and torsion (n=0) waves propagate. Also, several higher order (n>1), lobar modes exist around the pipe circumference above the cut-on frequency for each separate lobar mode. Finally, bending (n=1) waves propagate in the pipe, including the fluid.

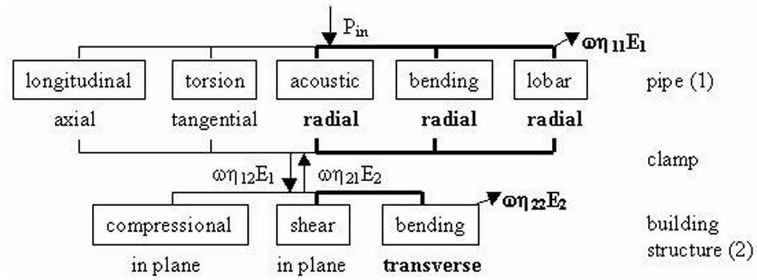

Figure 1: Sound transmission via pipe systems to building structures and rooms; SEA-model.

In order to describe the sound transmission from wastewater pipe systems to building structures and rooms in an accurate, but not too complicated way it is good to know which transmission paths play an important role and which paths can be neglected. To judge if SEA is a useful tool to describe the sound transmission the modal characteristics of the system elements have been checked. The mode number has been used as a decision criterion. In general, a mode number of at least 2 to 30 in a certain frequency band is required to be able to use SEA [1].
The mode numbers of the acoustic, bending and higher order modes in typical wastewater pipe systems are large enough to use SEA in the mid and high frequency range (at least two modes are present in each 1/3-octave band). The mode numbers of the longitudinal and torsion modes are much smaller and play a relatively small role in the total mode number. Therefore, these wave types are neglected in the sound transmission model for the moment.
In general, the mode number of the bending modes in typical building structures is large enough to use SEA, at least in the mid and high frequency range. Depending on the structures' material and dimensions, SEA can be used in the low frequency range also.
Further, it is assumed that the radial pipe vibrations of the bending and higher order modes and the forced vibration component of the acoustic modes inside the pipe are mainly responsible for the excitation of bending modes in the building structure and the direct sound radiation by the pipe. Therefore, at this moment the development of the statistical calculation model is focused on these transmission paths.

3 - LOSS FACTOR MEASUREMENTS

To measure the internal loss factors of a wastewater pipe and a building structure and the coupling loss factors of a typical pipe clamp, a measurement setup has been built in the laboratory. The loss factors can be used as input parameters for the statistical model. The measurement setup is based on the plate method (figure 2).
The setup consists of a concrete plate, freely suspended on springs (system resonance frequency: 5 Hz), and a representative toilet wastewater pipe, connected with each other by one clamp, consisting of a steel pipe ring and a steel rod. During the measurements the shakers are surrounded by a sound insulating box in order to avoid direct airborne sound transmission to the subsystems.

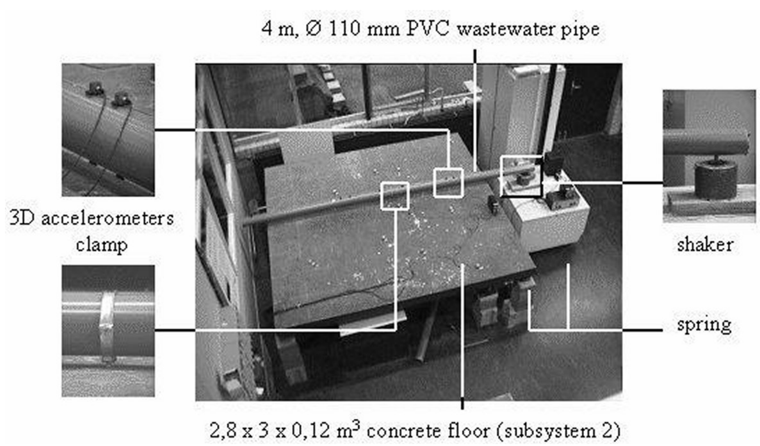

Figure 2: Experimental setup.

The loss factor measurements have been done for the most important transmission paths (see section

2). The measurements have been performed according to the Power Injection Method (PIM) [2]. The principle of PIM is shown in formula 1.

$$\frac{1}{\omega}\left\{\begin{array}{c} P_1 0 \\ 0 P_2 \end{array}\right\}\left\{\begin{array}{c} E_{11}E_{12} \\ E_{21}E_{22} \end{array}\right\}^{-1} = \left[\begin{array}{c} \eta'_{11}\eta'_{12} \\ \eta'_{21}\eta'_{22} \end{array}\right] \qquad (1)$$

The measurement procedure exists of two separate steps. In each step one of the subsystems is excited. The input power P is calculated out of the force and acceleration at the excitation point. The responses (velocities v; E = Mv^2 with M as the total subsystem mass) of both subsystems are measured each time. The internal loss factors (η_{ii}, η_{jj}) and coupling loss factors (η_{ij}, η_{ji}) have been derived according to formula 1.
After this procedure, the subsystems have been uncoupled. The structural reverberation time (T_s) of both separated subsystems has been measured, using the time-reversed technique and the internal loss factor has been derived for each subsystem. The matrix calculation according to formula 1 has been made more accurate by using these internal loss factor values as correction values.

4 - MEASUREMENT RESULTS

The measurement results are presented in figure 3.
When the pipe is excited the vibrations in the concrete plate are determined by the structure-borne sound path via the clamp. In principle, the directly radiated energy by the pipe to the building structure and eventually existing nearfields are included in the coupling loss factor. However, measurements have shown that the sound directly radiated by the pipe to the building structure is not important in this case.

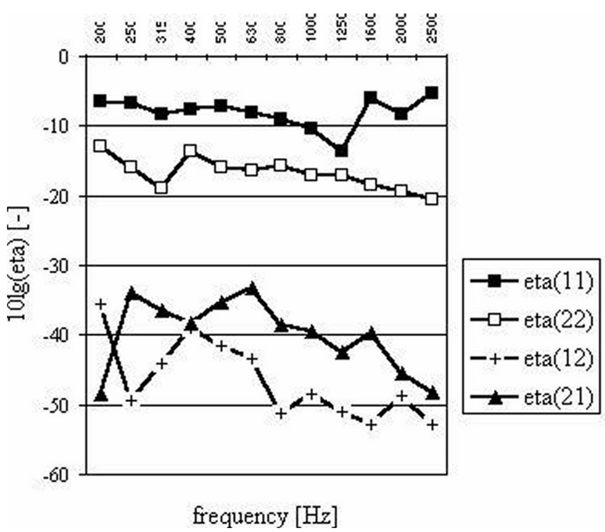

Figure 3: Measured loss factors; subsystem 1: pipe; subsystem 2: concrete plate.

As can be concluded from figure 3 the coupling loss factors are relatively low compared to the internal loss factors of both the wastewater pipe and the concrete plate. This is caused by the large mass difference of the subsystems and the small dimensions and number of clamps. The coupling between pipe and building structure can be characterized as weak, which is one of SEA's most important conditions.
In the experimental setup quite a heavy building structure is used. The radiation effect will be more pronounced while using a lighter building structure.

5 - REPEATABILITY AND REPRODUCIBILITY

In order to check the repeatability of the measurement method exactly the same measurements as described in the previous sections have been done a second time. For this purpose the pipe and building structure have been disconnected and connected again in order to investigate the influence of screwing the clamp again (without a defined number of turns). The measurement results are presented in figure 4.
To check the reproducibility of the measurement method the same measurements have been done with other source (shaker) and measurement positions. Also the clamp position has been changed. The measurement results are presented in figure 5.

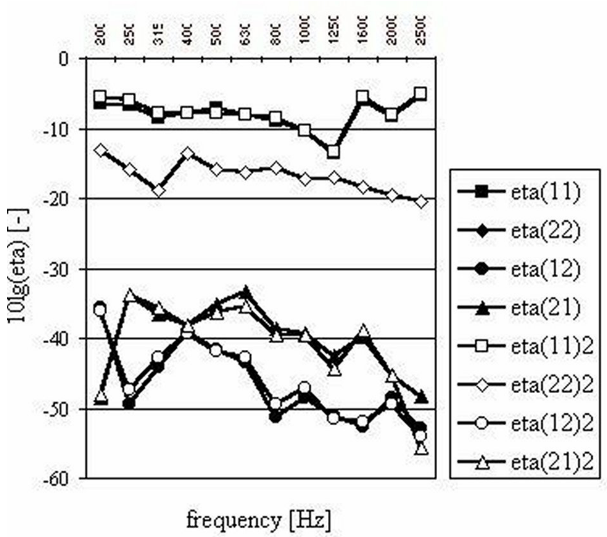

Figure 4: Measured loss factors; repeatability measurements.

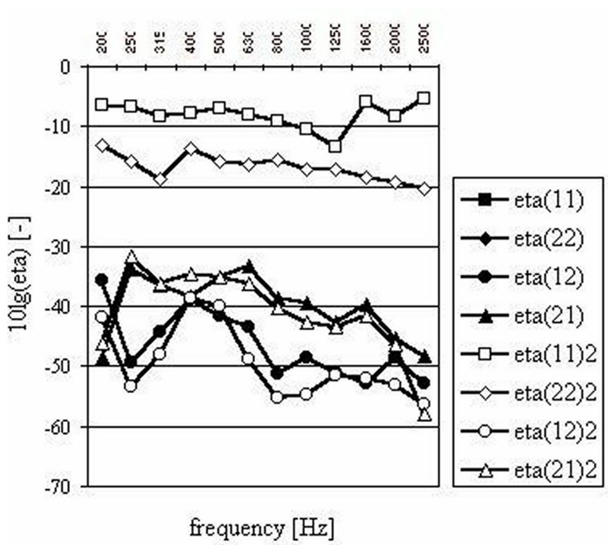

Figure 5: Measured loss factors; reproducibility measurements.

As can be concluded from figures 4 and 5 the measurements show good repeatability and reproducibility results. The maximum deviation between the repeatability measurements is 2 dB (for 2500 Hz: 5 dB). The maximum deviation between the reproducibility measurements is 6 dB (for 2500 Hz: 10 dB).

6 - COMPARISON WITH THEORY

In figure 6 the reciprocity relationship $\eta_{21}/\eta_{12}=N_1/N_2$ is checked. The N_1/N_2-lines are based on theoretical approximations and the measured values for N_1 and N_2.
As can be concluded from figure 6 the reciprocity relationship seems to be satisfied quite well, although there are big differences between the η_{21}/η_{12}-curve and the theoretical/measured N_1/N_2-curves for some 1/3-octave bands. So, in order to improve the reciprocity more research has to be done.

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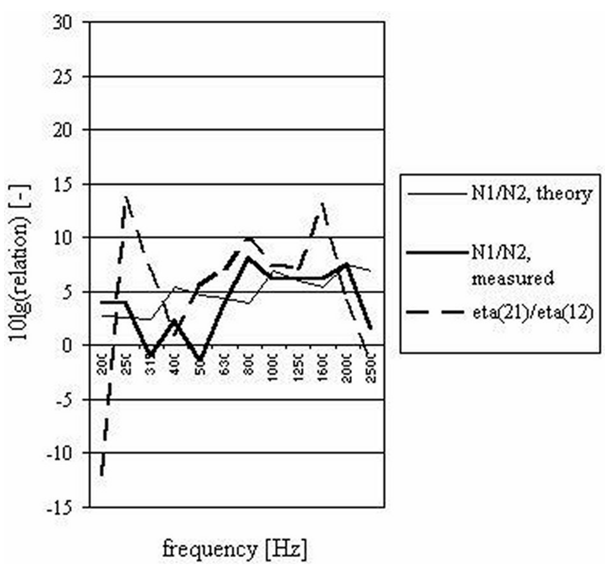

Figure 6: Measured loss factors; check reciprocity relationship.