Fluid-structure interaction in domestic piping systems

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Incentive

Knowledge of the fluid-borne sound power emission of a valve is not of great importance for the prediction of the airborne-sound immission caused by water appliances in domestic buildings. The structure-borne sound, due to fluid-structure interaction, is dominant. This so-called secondary structure-borne sound can become most important in the far field, as fluid-borne sound can travel long distances without significant reduction in sound power. In this paper the secondary structure-borne sound power emission of a complex pipe system is investigated along with the influence of the number of bends, as they serve as converter of plane fluid waves into structural waves on the pipe wall. The investigation is not limited to the pipe shell, but rather the response of the pipe system on a receiving structure is considered. A reception plate method is applied to circumvent problems that are inherent to the necessary decomposition of the different wave types when direct measurement on the pipe is required. The investigation aimed to establish the necessary number of bends for energy equipartition between the emitted fluid-borne and converted structure-borne sound. The method also provides input data on a power basis for a building propagation model.

Theory

The following considerations are based on the assumption that the pipe wall as well as the contained fluid can be assumed to be homogeneous and isotropic; moreover linear behaviour is assumed. The considerations are based on thin-wall theory with thickness-to-radius ratios $h/R << 1$.

Structural waves on a thin-walled pipe wall will generally travel in a helical pattern, as the deformations can be decomposed into harmonic components of circumferential orders $n=0,1,2,\ldots$ The components of most interest are $n=0$, which is a breathing mode of the shell and that of order $n=1$, which is a flexural mode. To each order n there are corresponding infinite numbers of theoretically axial wave numbers. These wave numbers can be pure real, pure imaginary or complex thus representing propagating, evanescent or quasi-propagating waves, respectively. It has been found that only few waves of orders $n=0$ and $n=1$ can propagate in a fluid-filled pipe well below its ring-frequency. In complex pipe systems with bends and other obstacles interaction takes place between the fluid- and structure-borne sounds. The fluid-structure interaction can be examined by analytical models such as the transfer matrix method (TMM) that is based on a thorough study of the propagation of fluid- and structure-borne waves in pipes or the FE method. All analytical models have in common that they require complicated modelling of the pipe system which must be limited in complexity and suffer difficulties in obtaining accurate input data, especially for the boundary conditions and the damping in the system. The models do not promise a way forward in the prediction of sound pressure levels from fluid-borne sources.

Measurements

Due to shortcomings of analytical methods for the prediction of sound pressure levels in buildings, an experimental approach was chosen for the study of fluid-structure interaction in domestic piping systems. A pipe system was designed with a total number of four pipe segments with different lengths. A straight pipe was first considered and then an increasing number of 90° bends were added to eventually produce a pipe system in three planes with a total of three bends. The pipe assembly was mounted on a three-dimensional concrete test rig. The method allows the reception plate power to be obtained and also offers the possibility of transforming reception plate power to installed power [1]. Figure 1 shows the measurement set-up with three pipe segments. While the fluid-borne sound power was always measured 1 m from the source, the structure-borne sound power emission was measured on the concrete reception plate.

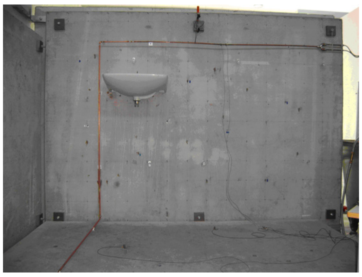

Figure 1: Pipe system with three segments mounted on three-plate reception rig.

The measurement of the fluid- and structure-borne sound powers showed similar behaviour for all investigated cases, but different peaks in the spectra due to resonances in the pipe systems of different length. They are due to resonances in the bending field of the pipe system and depend on the total pipe length of the system. This is also highlighted by the fact, that the dips are similar for the same total pipe length. A transmission coefficient for the conversion of fluid- to structure-borne sound power can be calculated from the relation of the fluid-borne sound power emitted by the valve and the resulting structure-borne sound power on the reception plate:

$$\gamma_{FBS/SBS,n} = \frac{P_{s,n}}{P_{f,n}} \quad (1)$$

The coefficient was calculated for the different cases and is shown in Figure 2. It is similar for all cases investigated with a general trend that could be described by a horizontal line up to 300 Hz, followed by a rising trend to about 1 kHz, which sets the upper limit for the frequency range of interest. Superposed are peaks in the spectra due to resonance effects in the finite pipe system and receiver plates.

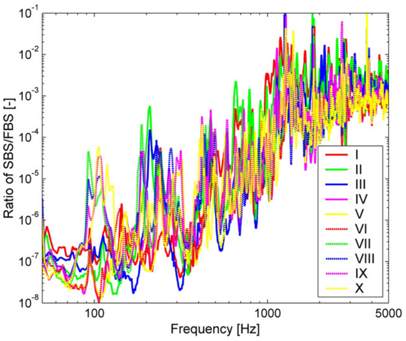

Figure 2: Transmission coefficient for investigated cases.

Energy equipartition is indicated in the straight pipe (case I), although fluid-structure interaction is usually not expected in a straight pipe. In the investigated case the first pipe segment consisted of two pipe segments that were connected by a bush. This connection is probably the cause for a first conversion from fluid- to structure-borne sound as might be the pressure transducers that were connected flush into the copper pipe to measure the fluid-borne sound power. Nevertheless, it seems to be appropriate to require one bend in a pipe system to secure sufficient energy mixing. The transmission coefficients provide a transformation of the fluid-borne emission of a pure fluid-borne sound source into the reception plate power, using equation 1.

In general, the resonant peaks in the transmission coefficient will limit the accuracy of sound pressure level predictions and are inherent to the proposed test method. Only randomising of results by investigating a large number of pipe configurations and connection positions on the plate would decrease the error.

Prediction for horizontal transmission

The sound pressure level in a receiving room was evaluated for a horizontal transmission situation using the prediction model of EN 12354-5 and compared with measurement. The piping consisted of three pipe segments. The measured sound pressure level in the receiving chamber showed broadband character with most of the energy around 500 Hz. The calculation of the sound pressure level in a receiving room requires the knowledge of the installed power into the building structure, in this case, the separating wall, according to [1].

The transmission coefficient from the measurement of two pipe segments with a 90° bend on the concrete reception plate was chosen, as this case was considered sufficient for satisfactory mixing of the fluid- and structure-borne sound energies. The product of the coefficient and the fluid-borne sound power of the actual pipe system in the test chamber was calculated according to eq. (2). Clearly, the obtained structure-borne sound power is that into the concrete reception plate. This value was transformed into the installed power, on the separating wall. Eventually the sound pressure level was calculated according to the prediction model of EN 12354-5. A comparison of the measured and predicted sound pressure level is shown in Figure 3 along with the A-weighted values calculated from the frequency range of 125 – 1,000 Hz. In general the agreement is acceptable but with significant differences due to resonant effects of the finite pipe system.

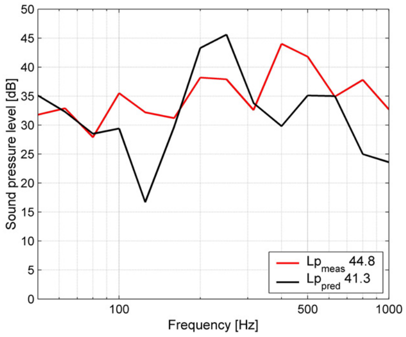

Figure 3: Measured and predicted sound pressure in-situ.

There is one further reason for the differences. The pipe system was attached with a total number of four connection points onto the concrete reception plate, while the mounting on the separating wall was accomplished with a total of seven connections. It was shown that the sound power level should be increased by 2.4 dB for such an increase in connection points [2]. This would yield an overall difference between prediction and measurement in the A-weighted value of 1.1 dB, which is quite promising.

Summary

It is shown, by introducing an increasing number of bends into a pipe system, that one bend along a pipe system is sufficient to obtain energy equipartition between the fluid- and structure-borne sound. A transmission coefficient is proposed that allows the structure-borne sound power into a receiving plate to be obtained from the fluid-borne sound power of a source. The sound pressure level in a receiving room, caused by a pipe system with valve on a separating wall was predicted and measured. The obtained results are promising and yield similar spectra and comparatively small differences in the A-weighted value of the structure-borne sound power, except for increased differences at distinct frequencies that are caused by resonances in the finite pipe system.

Literature

[1] M. Späh, H.-M. Fischer, B. Gibbs: “New laboratory for the measurement of structure-borne sound power for sanitary installations”, Forum Acusticum, (2005)

[2] T. Alber, PhD-thesis, University of Liverpool, (2006).