Determination of the fluid-borne sound power of valves using intensity techniques

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Incentive

At present, the acoustical behaviour of valves and water taps is quantified according to methods contained in ISO standard 3822. It has been shown by basic considerations that the physical assumptions of this approach inevitably result in shortcomings, which can compromise the comparability of test results gained in different test facilities [1]. Further, it has been made known that the output from this standardized measurement, the L_{ap}, in many cases will not give an appropriate description of the acoustic performance of valves and taps when installed. As a consequence the L_{ap} cannot be considered as a reliable basis for prediction of the appliance noise in the field. This has important consequences for the new prediction models of EN 12354-5.

Approach

The shortcomings in ISO 3822 have led to a new approach to describe valve noise in terms of power. The structure-borne sound power of valves can be determined using the free velocity and mobility approach [2]. The proposed method to obtain the fluid-borne sound power of a valve is the measurement of the sound intensity in the pipe.

Theory

In typical pipes in housing only plane waves can propagate through the fluid, in the frequency range of interest, since the cut-off frequency for higher order acoustic modes is well above 10 kHz. Therefore the fluid-borne emission of valves can be obtained by intensity techniques, because a semi-infinite condition can be acquired either by an anechoic liquid termination or by using a flexible pipe as termination. The latter has been chosen in this study, so that the fluid-borne sound power can be obtained as a product of sound intensity and cross-sectional area of the measurement pipe.

The sound intensity is the time-averaged product of the pressure and the particle velocity and can be obtained using the following equation:

$$I = -\frac{1}{\rho\omega\Delta r}\operatorname{Im}\left[G_{AB}\left(p_A, p_B, f\right)\right] \tag{1}$$

with G_{AB} being the cross-spectral density of the signals and Δr the distance between the transducers.

Errors in sound intensity measurements

Generally errors can be divided into bias (inherent) errors and random errors [3]. Random errors can be reduced by increasing the effort during the measurement while the two bias errors are inherent due to the finite difference approximation and depend strongly on the chosen separation distance Δr and the frequency range.

Random errors

The random error in sound intensity measurements is determined by the random error in the estimation of the cross-spectral density. The random error can be estimated by the standard deviation from N sample records for the measurement of the cross-spectral measurement:

$$\tilde{s}\left(\operatorname{Im}[G_{AB}]\right) = \left[\frac{1}{N}\left(1+\frac{1}{2\sin^2(k\Delta r)}\left(\frac{1}{\tilde{\gamma}^2_{pA,pB}}-1\right)\right)\right]^{\frac{1}{2}} \operatorname{Im}\left(G_{AB}\right) \tag{2}$$

with $\gamma^2_{pA,pB}$ being the squared coherence of an actual measurement.

Error due to finite difference approximation

This error concerns the limitation of the measurement method for higher frequencies. The systematic error due to the finite difference approximation for the intensity can be obtained according to Fahy [3]:

$$e(I) = -\left(2/3\right)\cdot\left(k\Delta r/2\right)^2 + \left(2/15\right)\cdot\left(k\Delta r/2\right)^4 \tag{3}$$

e(I) is the normalised error. For a maximum error of 0.5 dB, $k\Delta r$ should be less than 0,8. This means that for a liquid with a speed of sound of appr. 1400 m/s (water) and upper frequency limit 5.000 Hz the distance Δr should be less than 0.036 m.

Error due to phase mismatch

The second systematic error is due to the phase mismatch of the two measurement channels. Due to imperfect measurement system there is always a small delay between two measurement channels, which is referred to as phase mismatch. This error becomes apparent, when the time is short for the wave propagation between transducer A and B. The following equation with Φs being the transducer channel mismatch, can be used to calculate the normalized error due to phase mismatch between the sensing points:

$$e_{dB}(I) = 10\log\left(1+e(I)\right) = 10\log\left(1+\phi_s/kx\right) \tag{4}$$

The chosen distance of the transducer (Δr=30 mm) and the inherent phase mismatch of the measurement chain of 0.15° leads to bias errors shown in the next plot:

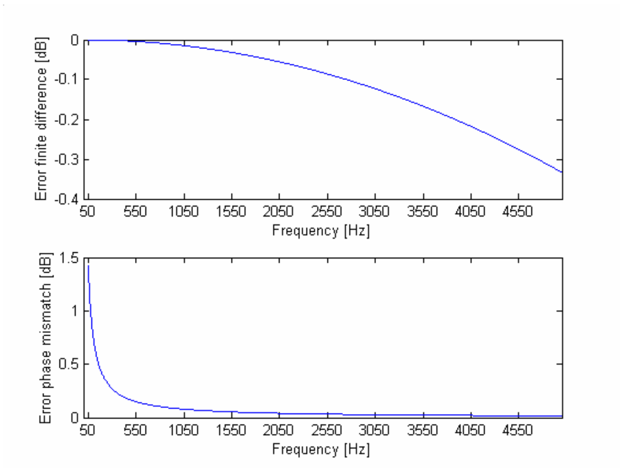

Figure 1: Error due to finite difference approximation (upper) and phase mismatch (lower).

Error due to reflections

Since the measurements have to be conducted for pressure of the order of 0.5 MPa, the pressure transducers had to be mounted into a copper pipe and a flexible pipe was attached to this rigid pipe to reduce fluid-borne sound from the water supply system. Therefore standing waves occur in the measurement pipe due to the impedance mismatch at the connection of the copper and the flexible pipe and need to be considered. In an ideal non-reflective pipe, the intensity could be calculated by only measuring the sound pressure level and the speed of sound, but in semi-infinite pipes the approach using the cross-spectral density needs to be considered. Furthermore the reflection coefficient R of the pipe termination has to be obtained [4]. The coefficient, with values between zero and one (one means total reflection) can be calculated with:

$$R_{fb} = \frac{G_{CC} + G_{DD} - 2 \cdot \left| \mathrm{Re}(G_{CD}) \cdot \cos\left(\frac{2\pi f \cdot \Delta r}{c}\right) - \mathrm{Im}(G_{CD}) \cdot \sin\left(\frac{2\pi f \cdot \Delta r}{c}\right) \right.}{G_{CC} + G_{DD} - 2 \cdot \left| \mathrm{Re}(G_{CD}) \cdot \cos\left(\frac{2\pi f \cdot \Delta r}{c}\right) + \mathrm{Im}(G_{CD}) \cdot \sin\left(\frac{2\pi f \cdot \Delta r}{c}\right) \right.} \quad (5)$$

Using the cross- and auto spectra's of the transducers. The reflection coefficient is shown in the following plot:

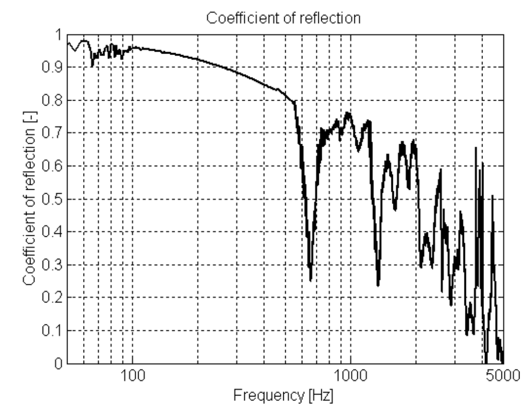

Figure 2: Coefficient of reflection

Finally the corrected value of the fluid-borne sound power can be calculated:

$$P_{fb} = \frac{\pi d_i^{\,2} I}{4\left(1 - R_{fb}\right)} \quad (6)$$

Measurement techniques and results

The following figure shows a comparison of 3 different single-lever mixers, a shower tap and the INS. Included is one quality tap (tap 2), a tap from a home store (tap 1) and two low-cost taps (tap 3 and shower). It can be clearly seen, that the quality tap has the lowest fluid-borne sound emission, while the cheap taps emit about 10 dB higher power levels. Furthermore it is obvious that most energy is emitted at about 250 Hz and the level than drops off sharply, with frequency, and can be neglected above 1kHz.

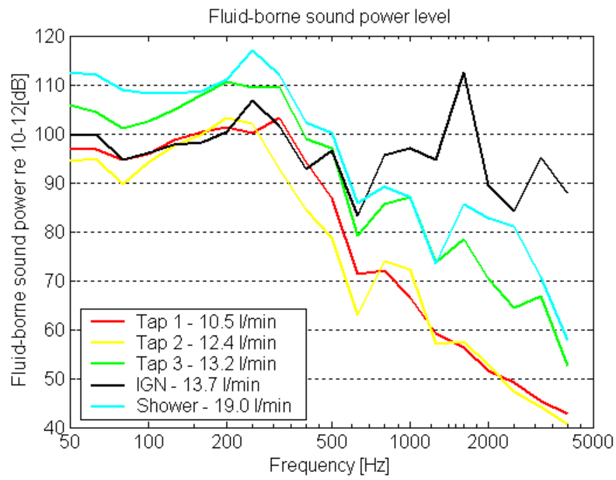

Figure 3: Result for the measured fluid-borne sound power

Conclusions

It has been shown that the proposed technique can be used to obtain the fluid-borne sound power of taps and similar valves as long as the pipe diameter can only support plane waves. In a next step it is necessary to investigate how the fluid-borne sound in the pipe converts into structure-borne sound on the pipe wall along the piping system, especially at bends. Finally the structure-borne sound power can be used as input data for a prediction model like EN 12354-5.

Literature

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