Proceedings of the Institute of Acoustics

Vibroacoustic power flow measurements in water-filled pipes

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1. INTRODUCTION

This paper describes a novel way of measuring the vibroacoustic power flow from a vibrational source connected to a water-filled pipe.

When dealing with noise or vibrational sources in connection with water-filled pipes, it is quite common to assume that all noise energy in the system propagates through the acoustic pressure field in the contained water and it can be quantified by the measurements of the internal acoustic sound power alone. The underlying assumption of this is that the walls of the pipe are very rigid and the water inside behaves like in an a hard walled circular duct. This is not necessarily the case for all pipe encountered in industrial applications, where thin or soft walled pipes are used for many different purposes. The compliant walls of the water-filled pipes make it possible to quantify the internal acoustic pressure by externally applied sensors without any direct contact with the water. This opens some possibilities for non-intrusive quantitative measurements of noise sources in connection with water-filled pipes.

The vibrations of the pipe walls are not only having implications for the sensing of the internal pressure but also for the entire transport of energy from the noise source. When the pipe walls are compliant, they will contribute to the power flow. Unfortunately, it is not as simple as just adding the contributions from vibrations of the pipe walls to the normal sound power in the fluid. The compliant walls affect the pressure field in the water, thus changing the sound power in the fluid. When dealing with the combined effect of compliant pipe walls and contained water, there are some complicated interactions that cannot be interpreted looking separately at the properties of the fluid or the pipe, respectively. The transport of energy in this combined system is dubbed the vibroacoustic power flow.

This paper shows some results obtained by analysing the vibrational response of a water-filled PVC pipe when excited by a radial point force on the pipe wall. The material of the pipe is chosen because it is soft enough to allow for significant radial vibration, but the methods are valid also for other heavily fluid loaded pipes, e.g. copper water pipes or even thin walled steel pipes.

2. MEASUREMENTS

The measurements presented are all made by external vibration sensors, namely accelerometers. As analysis of pipe vibrations involves modal analysis, the measurements made by the accelerometers are decomposed using circumferential Fourier decomposition. This technique allows the vibration of any point around the circumference of the pipe to be summed up through different modal contributions, e.g. breathing mode with axisymmetric motion of the pipe, beam bending of the pipe or ovalling of the pipe cross section. As an accelerometer only measures the vibration in a point, modal measurements with an accelerometer involves sampling in a number of points along the circumference with a subsequent post-processing. Research at the ISVR has developed a modal sensor of PVDF-film (based on the piezoelectric effect where the material produces a voltage when it is moved or vice versa) which allows the same types of measurements to be performed without any post-processing. It is, however, not employed for this work.

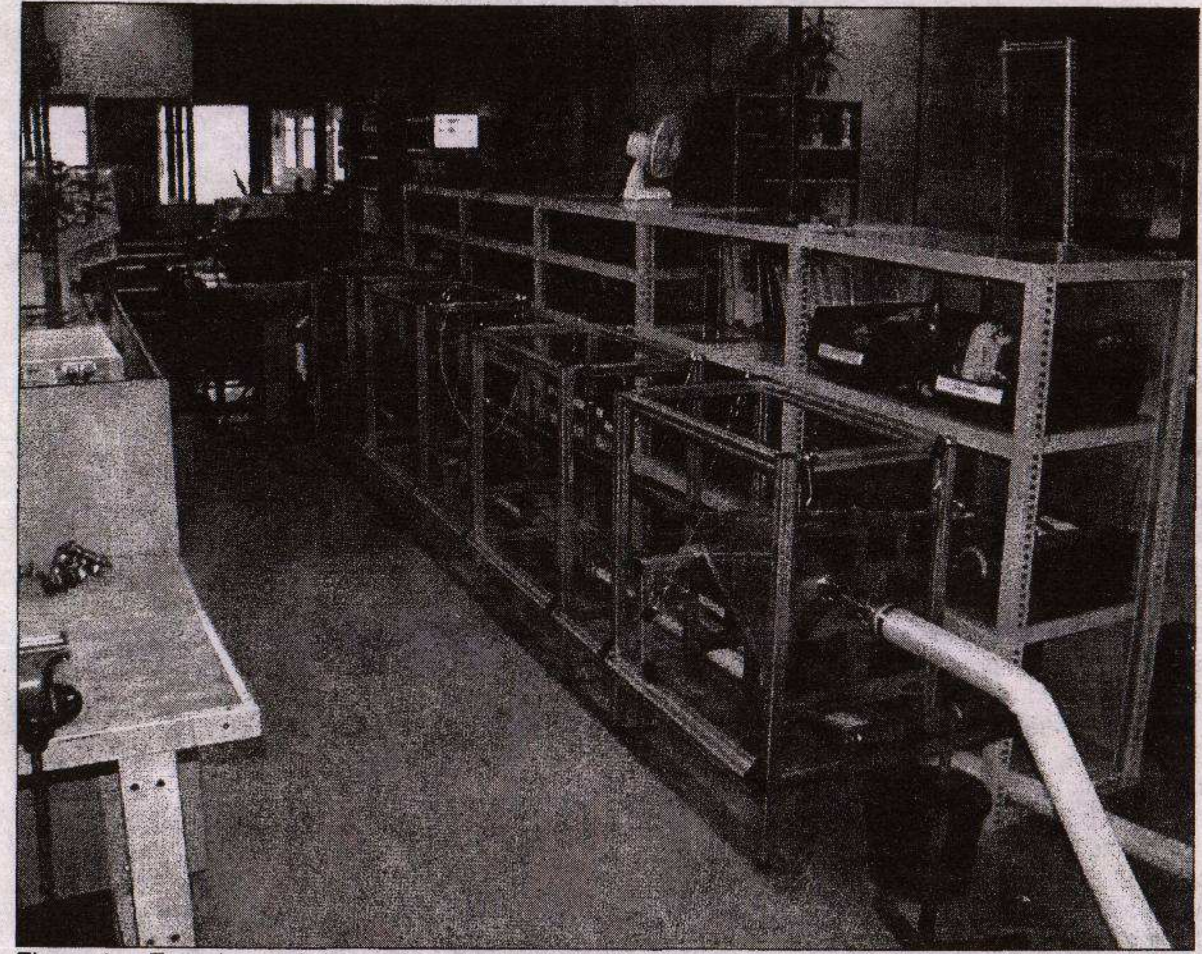

Figure 1. Experimental rig used to measure the vibrations of a water filled pipe excited by a radial point force from a vibration exciter. Noteworthy features are the anechoic terminations in either end of the 5 meter PVC measurement pipe.

The experiments are conducted on the experimental rig in figure 1. This rig has a 5 m long PVC pipe with an outer diameter of 63 mm and a wall thickness of 1.8 mm suspended in a number of strings to isolate it from external vibrations. As the measurement principle used is based on mathematical modelling of an infinite fluid-filled pipe, a trick is used to make the pipe appear infinite to both the noise source and the measurements. The trick is an anechoic termination that removes any vibroacoustic energy from the system before it reaches the end of the pipe, thus removing any potential standing waves. The ends of the pipe are embedded is a wedge shaped sandbox so the energy of the vibrations of the pipe walls is dissipated in the sand. A rubber hose is connected to the measurement pipe through an impedance matching pipe section just after the sandbox. The rubber hose dissipates the energy in the fluid pressure waves.

3. RESULTS

On the following pages are some figures, showing results from the measurements of the vibrational response of a PVC pipe when excited by a radial point force. All the graphs shows the measurements using a solid curve and theoretical predictions using dots. Note that both the frequency axis and the response axis are logarithmic, but not in dB.

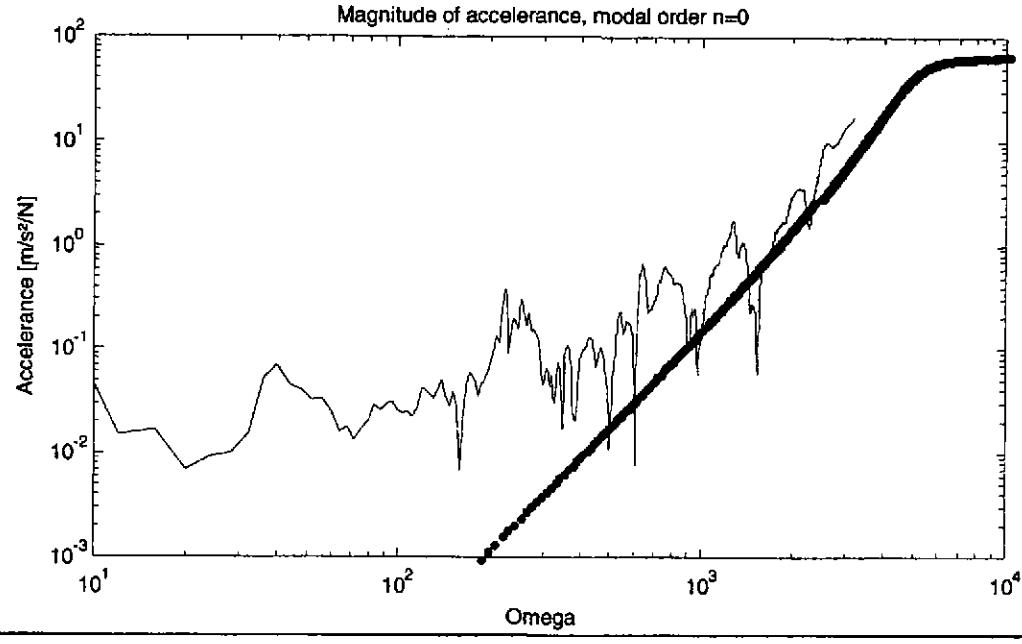

Figure 2. Magnitude of modal accelerance of the n=0 (breathing) mode at an axial distance of 150 mm from the point of excitation. The accelerance is the measured acceleration divided by the measured input force, i.e. the acceleration per unit input force. The N=12 indicates that the modal decomposition was made using 12 accelerometer positions around the circumference.

The dotted curve is predicted using a numerical model of an infinite water-filled pipe while the solid curve is the measured curve. While the agreement is fair at high frequencies, it seems quite bad at low frequencies. This is however, an artefact from the measurements technique, as the modal decomposition with accelerometers cannot discriminate modes perfectly. When placing the accelerometers around the circumference during the measurement, small errors of placement result through the post-processing in large relative errors in the modal response of the modes with a small response, although the absolute magnitude of the errors is very small indeed. This phenomena is dubbed modal leakage, as accelerance apparently 'leaks' from one mode to another.

A radial point force is very efficient in exciting the bending mode of the water-filled pipe and this mode therefore dominates the response of the breathing mode at low frequencies. From figure 3 it can be seen, that the measured accelerance for the bending mode at 100 Hz is approximately 0.6 m/s²/N, while the measurement for the breathing mode is approximately 0.03 m/s²/N, corresponding to a modal discrimination factor of approximately 20. The peaks in the measured accelerance for the breathing mode can be related to the behaviour of other modes. E.g. can the peak at approximately 200 Hz be related to the cuton of the n=2 mode. The accelerance of the n=2 at cuton is approximately 30 m/s²/N, while the modal leakage results in an apparent modal accelerance for n=0 of approximately 0.2 m/s²/N, corresponding to a modal discrimination factor of approximately 150.

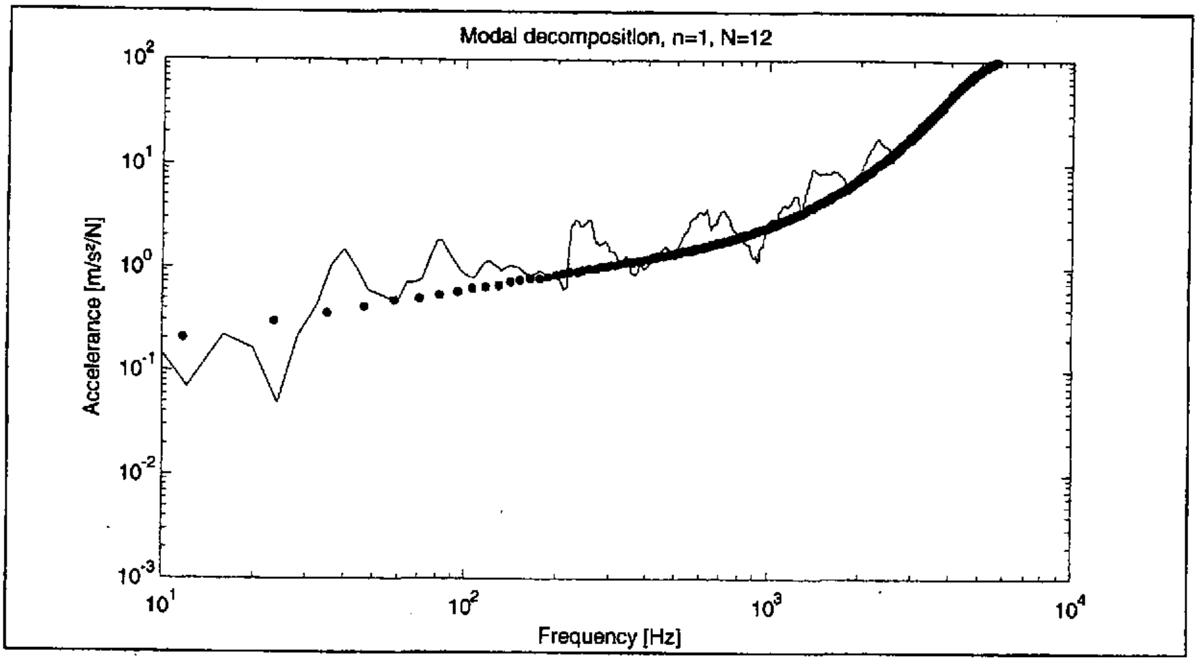

Figure 3. Magnitude of modal accelerance of the n=1 (bending) mode 150 mm from the source of vibration. Again is the dotted line the theoretical prediction while the solid line is the measured accelerance.

The comments from the n=0 accelerance regarding modal leakage also apply here, where the cuton of the n=2 mode results in a peak at approximately 200 Hz and likewise for the cuton of the n=3 mode at approximately 600 Hz. The modal leakage seems smaller in this mode, but this is mainly due to the significant response of the bending mode itself, thus making the relative impact smaller.

However, the peaks below the cuton frequency of the n=2 mode are not related to cuton of other modes, as the n=2 mode is the mode with the lowest cuton frequency. Instead, these peaks indicates standing waves in the axial direction,, with the characteristic peak-and-trough appearance of a resonance. The anechoic termination is supposed to remove any reflections from the end of the pipe, but apparently it is not very efficient at low frequencies. This is hardly surprising as the anechoic termination is only 0.8 m long while the bending wavelength at 100 Hz is close to 10 m. If better low frequency performance of the measurement of the bending mode is required, it is necessary to use a longer pipe combined with a larger anechoic termination.

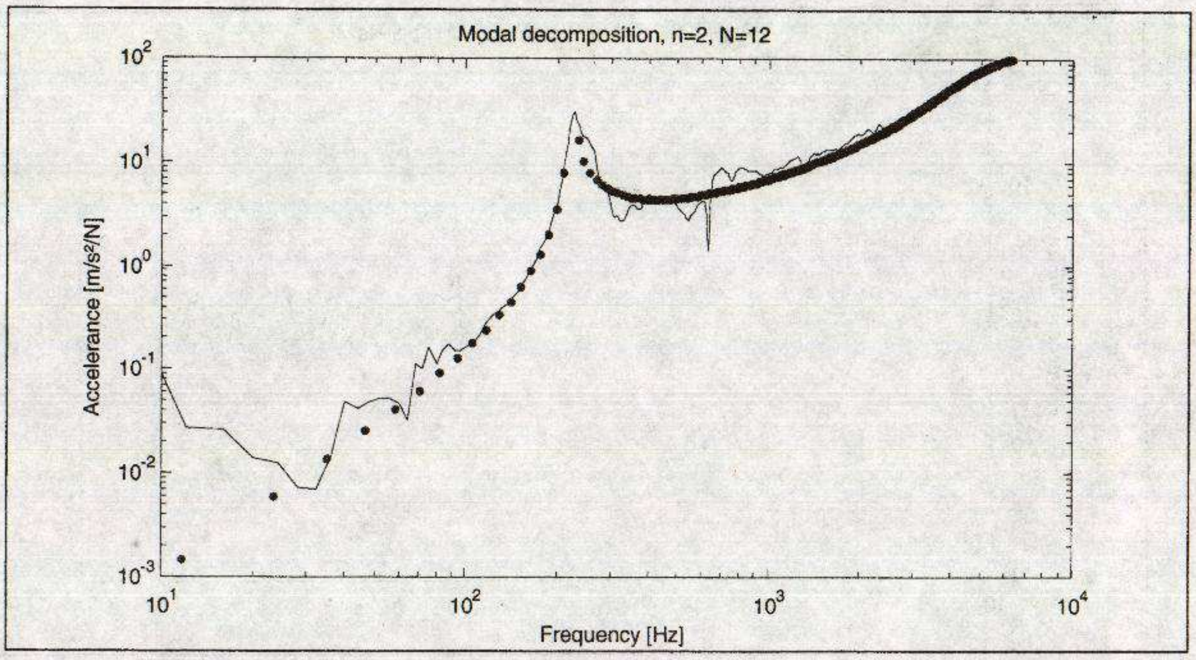

Figure 4. Magnitude of modal accelerance of the n=2 (ovalling) mode, 150 mm from the source. The n=2 mode is the first mode not cuton from zero frequency. At low frequencies, the modal accelerance is quite small, but near the cuton frequency the accelerance raises sharply. There is very good agreement between the theoretical prediction and the measurement.

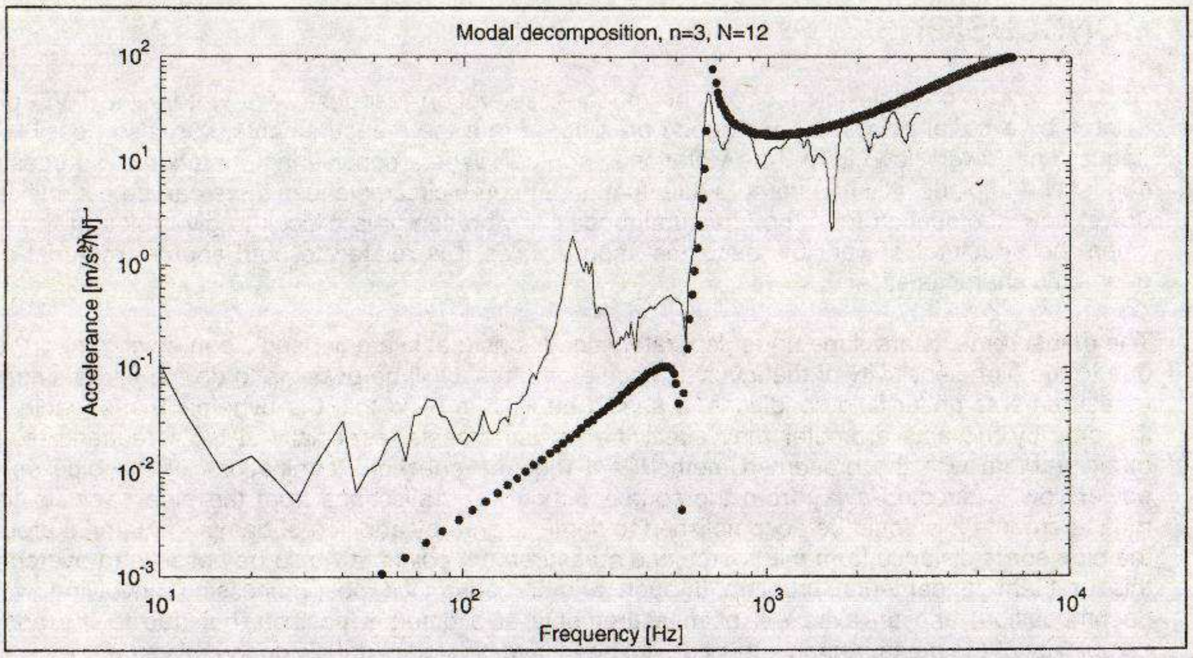

Figure 5. Magnitude of modal accelerance of the n=3 (teddy bear) mode, 150 mm from the source. The modal leakage from the cuton of the n=2 mode is evident. The agreement is not quite as good as for the n=2 mode, as the cuton 'peak' is not resolved fully and there is a slight drop in the measured curve at high frequencies. This is probably due to the damping of the pipe material as PVC has a rather high damping ratio of approximately 3 %.

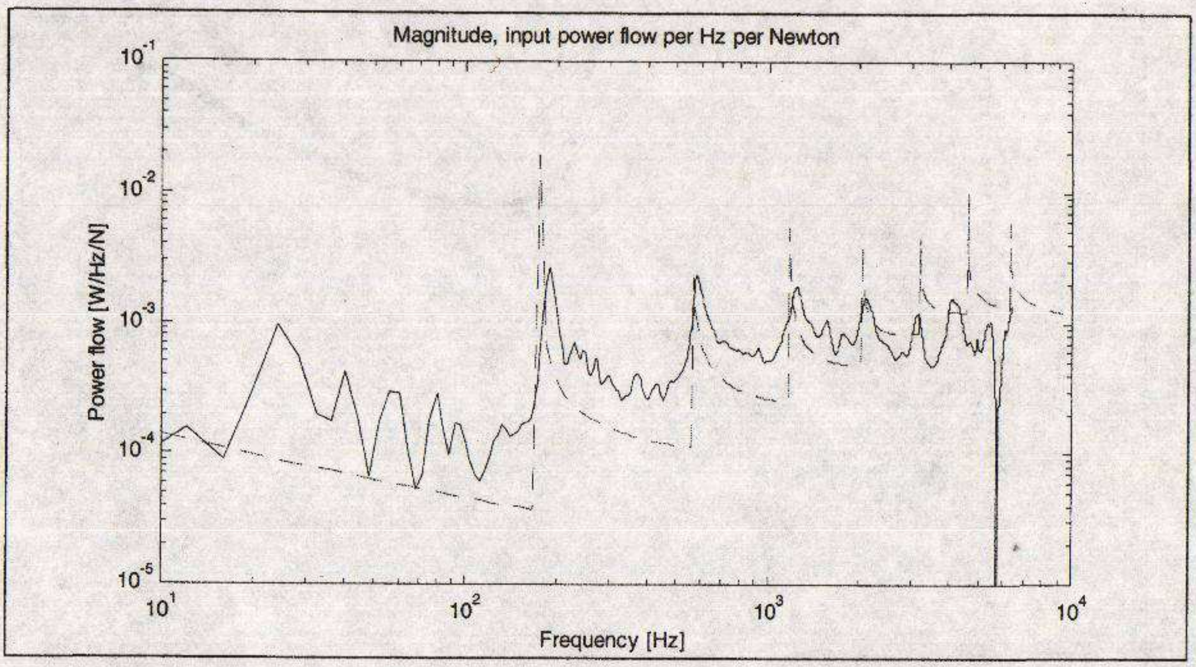

Figure 6. Power flow input from the point force to the water-filled pipe. The broken line is the predicted magnitude of power per Hz put into the water-filled pipe per unit input force and the full line is the corresponding measurement. The agreement is fair, with obvious problems at low and high frequencies, as discussed for the accelerance measurements.

CONCLUSIONS

As shown, it is possible to measure the modal acceleration response of a water-filled PVC pipe excited by a radial point force with good precision. From the measurements, it is also possible to deduce a power flow from the vibrational source. When considering vibrational sources in connection to pipes, it is important to note that under some circumstances there can be a significant power flow contribution from the structural modes of vibration. It is difficult to give rules of thumbs when the structural power flow becomes important, as it is related to both source, material and geometric characteristics.

The measurements are done under laboratory conditions (i.e. in a quiet and clean environment), but due to the high sensitivity of the involved accelerometers it will be possible to do the same kinds of measurements under field conditions. It should be kept in mind that the dynamic mass loading of the pipe by the accelerometer may affect the measurements, especially at high frequencies. An other problem with the presented method is it requires anechoic terminations of the pipe so all power flow is directed away from the source without any reflections from the pipe ends. In field measurements this could be accomplished to some degree by addition of damping material around the pipe some distance from the source and measurement points. It would be possible to overcome this problem fundamental problem through a more advanced post-processing (involving wave decomposition) and an extra set of measurements at a different position, but due to the added complexity of the measurements this has not been investigated in details during this study.