Determination of sewer roughness and sediment properties using acoustic techniques

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Abstract Measurements have been carried out to determine the effect of porous sediments in a pipe on the attenuation and spectrum of the airborne acoustic field. The results show that the presence of even a relatively thin sandy layer results in a considerable increase in the acoustic attenuation over the broad frequency range. The measured value of the relative attenuation is in the range of 0.6 dB/m. The effect of the sediment on the acoustic spectrum is the reduction in energy of the propagating modes, which is an easily detectable phenomenon. These results pave the way for the development of the instrumentation for non-invasive characterisation of the parameters of sediments in wastewater systems.

Keywords Acoustic properties of pipe sediments; normal modes; sound propagation in sewer pipes

Introduction

The water industry uses mathematical models of sewerage systems to predict and simulate flows. These models are essential tools in the design process for rehabilitating existing ageing systems and assessing the propensity for flooding and discharges to watercourses. Bed sediments, pipe obstructions and general pipe roughness can considerably affect the theoretical predictions. Although many mathematical models can simulate these effects, accurate flow simulations still require accurate data about the conditions in sewers. The hydraulic performance of sewer systems is intrinsically linked to the roughness of the boundaries. Most sewers in developed countries suffer from some form of sedimentation, albeit transient in certain cases (e.g. Ackers et al., 1996). Sewers experience wall sliming from first use, and roughen with age. Taken together, the effects of sediments and wall roughness are to increase the resistance to flow, typically characterised by the effective roughness $k$. The latter is not a physical dimension, but is an “effective” measure, as if the boundary roughness were “equivalent uniform sand grains” and is related not just to the walls of the sewer but also to the behaviour of sewer sediments (consolidation, erosion) and the prevailing hydraulic conditions. Data pertaining to sediments and actual sewer roughness are still very limited, despite the importance for pollution management and effective downstream sewage treatment. Currently there are no means of determining in-situ, sewer sediment bed properties. Samples have to be extracted and tested in a disturbed state.

A major problem for sewer flow modellers, and hence sewer system operators, is to define the physical value of the roughness coefficient, $k$, given that it cannot be measured directly. Normally, “standard” values are selected based on published data or images, which are subjectively applied, requiring subsequent model refinement in the process of model verification. Where sediment deposits are present, and/or sewer wall damage exists, the process of assessing relative roughness can be costly and protracted, requiring the user to visually inspect the sewer from closed circuit TV recordings. However, judgements of sediment depth, intrusions and general roughness are subjective, and in addition, surveys are often obscured by the flow or abandoned because obstructions are impassable. Shape recognition techniques (Taylor et al., 1998) have also been investigated, to provide an
automatic transcription of the video image, but these are in their infancy and can only be used as far as vision and access permits. Although the application of acoustic techniques in sewers is now widespread to monitor velocity, level and depth of sediment, these instruments can provide only local information and need to be moved mechanically to obtain data over a larger area of sewer.

In the UK, the fundamental relationship used to link the effective boundary roughness with flow is the combination of the Darcy–Weisbach and Colebrook–White equations, which for the hydraulic gradient for circular pipes of diameter $D$ without sediments is given by (Ackers et al., 1996)

\[
\lambda = 4 \left( \log_{10} \left( \frac{k}{3.7D} + \frac{2.51v}{D \sqrt{2gDi}} \right) \right)^{-2},
\]

where $\lambda$ is the flow velocity, $v$ is the fluid kinematic viscosity and $g$ is the acceleration due to gravity. By careful measurement of hydraulic gradient in a controlled experiment (depth plus kinetic head upstream and downstream), it is possible to solve Eq. (1) for $k$ (e.g. Henderson, 1984). Where a bed exists, the calculation is more complex as it requires a partitioning of $\lambda$ between the various “wetted” surfaces in proportion to their circumferential lengths. Where sediment deposits exist, they simultaneously constrict the cross section of the sewer, and increase the effective boundary roughness, reducing the flow capacity. Currently measurement of in-sewer sediments has to be done manually, or by floating “imaging” systems down the sewer (e.g. Ashley et al., 1993). This only works where there is access and the flow depth is either not too shallow or not so turbulent that safety is compromised or equipment endangered. Measurement of effective boundary roughness can only be made subjectively by comparisons with published visual data. In some cases it is possible to “calibrate” a sewer for $k$, by collecting lengthy periods of hydraulic data, using at least two sets of sonar sensors, one at either end of a length, together with velocity information at each location. The determined value of $k$ will then be an “average” value as it varies with depth of flow, and may be “partitioned” into bed, grain and wall components (e.g. Henderson, 1984). An example is shown in Figure 1 (Wotherspoon, 1994).

There has been a considerable amount of work on sound propagation in ducts, channels and waveguides that is relevant to pipes and sewers (e.g. Nechaev, 1982; Lapin, 1996; Rienstra, 1999). Many of these studies rely on the method of normal mode decomposition and provide a good theoretical basis for the development of instrumentation which can use the acoustic response of a duct for the global characterisation of its physical and geometrical properties. Instruments have already been developed to determine large variations of the cross-section in ducts and also the acoustic impedance, using the method of acoustic reflectometry (e.g. Sharp, 1996).

This paper reports on the general concept of the idea of the normal modal decomposition and on some preliminary results from pilot scale model experiments. The results demonstrate that the proposed acoustic method is very sensitive to the variation in the boundary conditions of an air-filled pipe. It is shown that a simple acoustic experiment can provide comprehensive information on the scale of the sedimentation in a pipe and on some of the characteristic parameters of the sediment.

**Theoretical background**

The method of normal mode decomposition assumes that a source of sound and the receiver are deployed in an air- or fluid-filled duct for which the boundary conditions are partly

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unknown. If the cross-section of the duct is large in comparison with the acoustic wavelength, then this duct represents a two-dimensional waveguide which can support several acoustic waves (normal modes) which travel in the pipe at different velocities and different angles. In this case it is common to express the acoustic pressure at any point in the pipe via a superposition of the normal modes

$$p(x,y,z) \equiv \sum_{m,n=0}^{N} A_{mn} \psi_{mn}(x,y)e^{i \zeta_{mn} z}$$

(2)

where $\psi_{mn}(x,y)$ is the modal eigenfunction, $A_{mn} = \psi_{mn}(x_0, y_0)$ is the modal excitation coefficient and $\zeta_{mn}$ is the modal wavenumber for the $(mn)$th mode. The eigenfunction $\psi_{mn}$ depends on the cross-sectional shape of the pipe, the depth of fluid, flow velocity and on the boundary conditions. In any pipe there are an infinite number of modes. A finite number of modes, which are called propagating modes, can travel in the pipe with little attenuation. These modes correspond to acoustic waves, which travel at an angle $\theta_{mn}$ (see Figure 2).

Here $k_0$ shows the direction for modal propagation and denotes the wavenumber in the fluid. The amplitude of evanescent modes is reduced exponentially with distance and often neglected in calculations. This formulation is general and stands for fluid- and air-filled pipes. In simple cases, for example, for a pipe of a circular cross-section these functions are given by
\[ \psi_{mn} = \cos(m\phi) J_m \left( \frac{\pi q_{mn} r}{a} \right) \]  

where \( J_m(z) \) is the Bessel function of order \( m \); \( r \) and \( \phi \) are the polar co-ordinates about the central axis of the pipe; \( \zeta_{mn} = \sqrt{k_0^2 - \chi_{mn}^2} \); \( \chi_{mn} = \pi q_{mn}/a \); \( a \) is the radius of the pipe and \( q_{mn} \) is determined from the boundary conditions (see Morse and Ingard, 1986). If the cross-section, boundary conditions or flow characteristics are complex, then the above quantities can be predicted numerically using the finite element method (e.g. Eversman and Astley, 1981).

In a pipe with a regular cross-section the modal eigenfunctions \( \psi_{mn} \) and wavenumbers \( \zeta_{mn} \) do not depend on the distance from the source \( R \), and the acoustic energy of the modes is conserved within the mode itself. If the cross-section of the waveguide and the boundary conditions are range-dependent, then the shapes of the normal modes are range-dependent as well and individual modes are coupled. Similar phenomena occur in the presence of an unsteady flow of the fluid in the waveguide. The perturbations in the fluid flow are responsible for the variations in the amplitude and phase of the measured acoustic pressure and these are detectable in many cases.

If the dimensions and the shape of the pipe, the acoustic boundary conditions on its walls and the parameters of fluid flow are known then the modal eigenfunctions and wavenumbers can be predicted. Acoustic measurements can be carried out using a continuous acoustic stimulus or short impulses. The propagating modes can be detected using several receivers, which are distributed in the pipe or a single receiver and planned signal processing methods. It is common to use the matched field processing algorithm (e.g. Hermand, 1999), which can be employed to relate the variations in the modal velocity to the variations in the boundary conditions and the parameters of the fluid flow. In this analysis the initial (unperturbed) amplitude and the phase in the acoustic response are predicted for a particular cross-section and boundary conditions which are locally measured or predicted. In the case of the continuous acoustic stimulus, the modal wavenumber \( \zeta_{mn} \) is measured by comparing the phase in the received signal with that of the signal from the reference receiver. If the stimulus is a short pulse, then the same result is achieved by measuring the travel time for the mode of this index.

**Experimental procedure**

A 1.5 m section of a 75 mm plastic pipe was used to investigate the sensitivity of the proposed acoustic method. The pipe was selected so that the section represented a scale model of a real sewer at a scale of about 1:20. The wall of the pipe was 3 mm thick and the density of plastic was sufficiently high (around 1,150 kg/m³) to assume that acoustic coupling between the airborne sound in the pipe and the mechanical vibration in the walls was negligibly small. The pipe was bisected to allow easy deposition of the controlled amount of sediment. In the experiments the two halves of the pipe were held together with adhesive tape.

Short pulses were generated using a 25 mm dome tweeter which was driven by a maximum length sequence signal processing system (MLSSA). The source provided a sufficient acoustic energy output throughout the considered frequency range of 1,000–40,000 Hz. A 1/4" condenser microphone was mounted in two circular disks of porous foam in the middle of the pipe 1.2 m away from the source. The ends of the pipes were left open. The conditions for sound propagation were tested in the empty pipe and in the pipe partially filled with a 4–8 mm layer of sand.

**Discussion of the results**

Time and spectral analysis was carried out to determine the effects of the sediment on the acoustic attenuation and frequency composition of the transmitted acoustic field. Two
major effects associated with the presence of the permeable layer have been detected: the increase in the acoustic attenuation (see Figure 3) and variation in the acoustic spectrum (see Figure 4).

In Figure 3 the sound pressure level is presented as a function of the propagated distance which includes the multiple reflections from the pipe ends. The data suggest that even relatively small amounts of sediment noticeably affect the sound attenuation in the pipe. They also suggest that for a relatively short section of the pipe this change is easily detectable. These results give an indication of the effective distance over which the change in the acoustic attenuation is effectively measurable. Since modern data acquisition and signal processing systems can provide < 1.0 dB resolution, then the effective distance should be within several metres in the case of pipes typical of the investigated cross-section.

Figure 4 present the spectrograms (spectral composition of the acoustic signal as a function of time) for the empty pipe and for the pipe with a layer of sand, respectively. In the case of the empty pipe (see Figure 4 (a)), there are two clearly visible propagating modes in the acoustic spectrum, for which the attenuation is relatively low. The frequencies of these components can be predicted from the boundary conditions (e.g. Morse, 1986). The predicted values (1st mode: 5,530 Hz, 2nd mode: 10,100 Hz) closely agree with those determined from the experiment (see Figure 4 (a)). The reflections from the pipe ends are clearly visible in the form of vertical periodic lines (see Figure 4 (a)). Similar reflections will occur if there are lateral connections in the pipe or if the cross-section of the pipe varies along its length. In this case a proportion of the acoustic energy is scattered and reflected. This phenomenon can be used for the detection of laterals in the pipe or blockages.

Figure 4 (b) shows the spectral variation of the acoustic response of the pipe filled with a layer of sand. The effect of the sandy layer is observed throughout the considered frequency range. There is a noticeable decrease in the energy of the 1st mode and a very pronounced reduction in the case of the 2nd mode as well as the other spectral components, which is a result of the acoustic absorption and roughness in the layer of sand. At shorter
distances there is a considerable reduction in the sound pressure level at certain frequencies which are related to the geometry of the pipe, layer roughness and layer absorption (e.g. 30, 32.5, 3 and 37 kHz in Figure 4 (b)).

**Conclusions**

The experimental results suggest that the presence of porous, rough sediment in a pipe results in a measurable increase in the acoustic attenuation in the broad frequency range. The measured value of such an increase for a layer of sand is in the range of 0.6 dB/m. The amplitude and the position of individual minima and maxima in the acoustic spectrum are sensitive to the boundary conditions. The effect of the sediment on the acoustic spectrum is easily detectable. The results obtained can be used to develop instrumentation for on-line, non-invasive characterisation of parameters for boundary roughness and sediments in wastewater systems.

*Figure 4* Spectrograms of the relative sound pressure level as a function of the propagated distance and the frequency in the empty pipe (a) and the pipe with a layer of sand (b)
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References