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Cover Page Footnote
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An Acoustic-Based Approach for Condition Monitoring of Pipes

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Running Title: An Acoustic-Based Approach for Conditioning Monitoring of Pipes

Abstract

Polyvinyl chloride (PVC) pipes are extensively used in municipal sewer systems. As the sewer piping networks are aging, PVC pipes are prone to developing cracks that can release toxic effluents into the environment. Traditionally, to monitor defects in PVC pipes, utility operators pass a close circuit TV (CCTV) camera mounted on a guided vehicle through the pipe. The video is observed by a trained operator who records condition of the pipe. This arrangement, suffers from two major limitations. One, it is expensive due to complex set up and second, if a pipe is blocked the guided vehicle cannot pass through its entire length. A more economical and robust system is needed that can reliably detect cracks in sewer pipes. Our approach is based on measuring acoustic signal attenuation in a cracked pipe and comparing it with attenuation in a pipe with no cracks. This study is work in progress and preliminary results from laboratory test setup are presented. Testing in actual sewer installations is being planned and results will be reported in future.

Introduction

Effective preventive maintenance on aging sewer system infrastructure to mitigate sewer system overflows (SSOs) is a major challenge for the utility operators in the United States (US). Timely detection of potential defects in sewer piping networks can significantly reduce the frequency and volume of unauthorized effluent discharges. It can also result in monetary savings to the operators due to reduced number of emergency responses and other unexpected costs. Better knowledge of structural health of underground assets also enables the utility operators to prioritize deployment of corrective maintenance resources. The condition assessment of sewer piping networks is performed by collecting data through observation, direct inspection, investigation, and monitoring. Analysis of collected data helps determine structural and operational condition of the sewer pipelines.

Historically, vitrified clay pipes (VCP) were used in municipal sewer piping networks. The VCP suffered from structural failures in expansive clay soils. Failures at the VCP pipe joints were also common due to root ingress resulting in cracked pipes. The VCP were replaced by PVC pipes in sewer installations. The PVC pipes offer advantages due to their low cost, corrosion resistance, light weight and comparative ease of installation. Despite these advantages, PVC pipes are also prone to failure due to multiple reasons and need periodic condition assessment to prevent SSOs and leaks.

Present industry standard for sewer monitoring is based on passing a robot mounted with a closed-circuit television (CCTV) camera through a pipe to assess its condition. The video output from the camera is observed by a human operator who records annotates his observations on the video. Condition assessment from video signals is indirect and heavily influenced by capabilities of the camera and observational skills of the operator. Another major limitation is that robot may not be able to go through full length of the pipe due to blockages, structural defects, or other obstacles. The CCTV based systems also require an off-road capable vehicle, electric generator, a camera mounted robot, cable with reel and a custom software with a control system. These systems are, therefore, expensive and crew-hour intensive.

The present study proposes an approach to detect cracks in a pipe by measuring attenuation of a propagating acoustic signal. A rigid-walled circular pipe (such as a circular PVC sewer pipe) behaves as a waveguide when excited by an acoustic signal. The existence of a crack introduces an impedance mismatch in the signal path that causes attenuation and reflections. A pipe with cracks suffers greater attenuation and reflection compared to a pipe with no cracks. Analytical modeling of acoustic signal propagation in live sewer networks is very complex and may be intractable due to presence of laterals and other random variable phenomenon (such as varying level of water, root ingress, rodents, blockages, and pipe defects etc.). This study, as a preliminary work, focuses on using an empirical based approach to detect cracks by measuring difference in signal attenuation between a pipe with cracks and a pipe without any cracks.

Previous Work

Previous work on designing a real-time pipeline monitoring application using acoustic signal has led to the development of portable and rapidly-deployable SL-RAT^{TM} (Sewer Line Rapid Assessment Tool) and SewerBatt^{TM} systems (Murray *et al*. 2014a,b). A research group at the University of North Carolina at Charlotte (UNCC) collaborated with Charlotte Water to determine the feasibility of an acoustics based pipeline condition monitoring system to detect blockages in pipes and prevent SSOs. This work led to further research and development by a technology startup company that produced SL-RAT^{TM} (Howitt 2012; Fishburne 2010). The project also provided valuable field data measured in operating sewer systems in Charlotte that was used for academic research (Khan 2013). The work was focused on developing deterministic and stochastic models of acoustic attenuation to characterize signal propagation in sewer pipes in the presence of random variable numbers and lengths of side branches (Khan 2016; Khan 2017).

The SL-RAT^{TM} system works by transmitting an acoustic signal through the pipe from a manhole. The received signal is measured at the next manhole and processed to determine signal attenuation caused by blockages in the pipe. Based on the measured signal attenuation, a numerical score between 0 to 9 is assigned to a pipe segment (where 0 = fully blocked and 9 = clean). The score can be used by utility operators to plan future maintenance interventions. The SL-RAT^{TM} does not detect the extent or location of cracks or other structural defects in a sewer pipes. Utility operators have to use CCTV system to investigate the pipe sections where structural defects are suspected based on SL-RAT^{TM} numerical scores (e.g. a pipe with a score of 5).

The SewerBatt^{TM} has been developed by a research group at the universities of Bradford and Sheffield in United Kingdom. The system is based on analyzing modes of acoustic signal propagation. The energy in the modes of reflected signal from blockages and other surface defects is measured to classify condition of the pipe (Horoshenkov *et al*. 2003; Podd *et al*. 2007; Yin *et al*. 2005). To deploy a SewerBatt^{TM} system, an acoustic transducer is inserted into the pipe which comes in contact with the raw effluent. It requires thorough cleaning after each use for the safety of operators. The system has been tested on live sewers during a technology demonstration for United States Environmental Protection Agency (USEPA) (Murray *et al*. 2014b). Results indicate that in pipes with multiple laterals most of the weak reflected signal is lost leading to false condition assessments requiring further inspection by a CCTV system (Murray et al. 2014b). The limitations in SL-RAT^{TM} and SewerBatt^{TM} systems underscore the need for further study into use of acoustic signals to monitor structural health of sewer pipes.

Theoretical Formulation

The sound pressure of an acoustic signal transmitted through a pipe is normally measured with respect to a reference pressure in terms of Sound Pressure Level (SPL) in decibel [dB]. For a travelling wave at distance d from the source, the SPL is given by (Blackstock 2000):

$$[SPL]_R = [SPL]_0 - \alpha d. \tag{1}$$

where $[SPL]_0$ is the reference SPL and α is attenuation coefficient representing signal loss in dB/m. The relationship in (1) can be used to determine the received SPL within a straight pipe with no laterals. The attenuation coefficient α is determined from the existing theoretical model given in (Khan 2016). The reference pressure is obtained from the measurement at the reference microphone.

The cracks add another a signal loss term (δ_T) in (1) and the propagation model becomes

$$[SPL]_R = [SPL]_0 - \alpha d - \delta_T. \tag{2}$$

The model in (2) can be used to measure additional loss in an acoustic signal due to cracks and other surface defects.

Materials and Methods

A diagram of the proposed test setup to measure attenuation from a crack in a pipe is given in Fig. 1. The acoustic signal comprising 22 tones at one-third octave band frequencies between 50 Hz – 10 kHz is generated using MATLAB^{TM} on a notebook which acts as a controller. The tonal frequencies are divided into three bands. A low frequency band comprising 7 frequencies between 50 Hz-200 Hz, a mid-frequency band

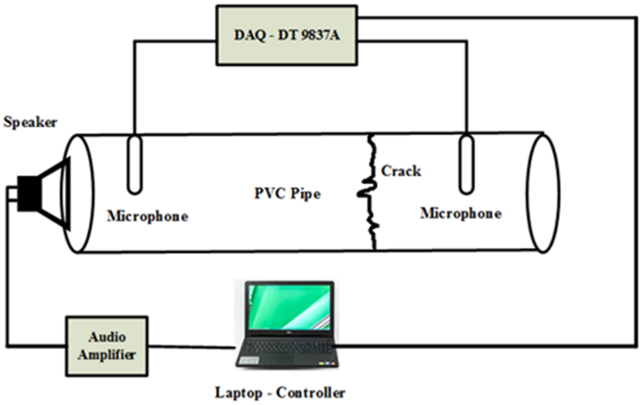

Figure 1: Laboratory Test Setup.

comprising 10 frequencies between 250 Hz- 2.0kHz; and a high-frequency band comprising 7 frequencies between 2.5 kHz to 10.0 kHz. The generated audio signals are amplified with a Samson Servo 200 Amplifier. A Tang Band (W4-1337SDF) 4" Titanium full range speaker coupled to one end of the pipe is used to transmit the audio tones through the pipe. A reference microphone (BSWA MPA 415) measures the reference signal and an output microphone placed at the other end of the pipe measures the received signal.

The difference between the signals measured at reference and output microphones gives the attenuation in the signal. A picture of the test set up is given in Fig. 2. The experimental set up includes two ten-foot sections of Schedule 40 PVC pipe (a section with a 3 mm half-diameter crack in the middle and a section without crack). The data from microphones is acquired using DT-9837A data acquisition (DAQ) module using DAQ toolbox in MATLAB^{TM}.

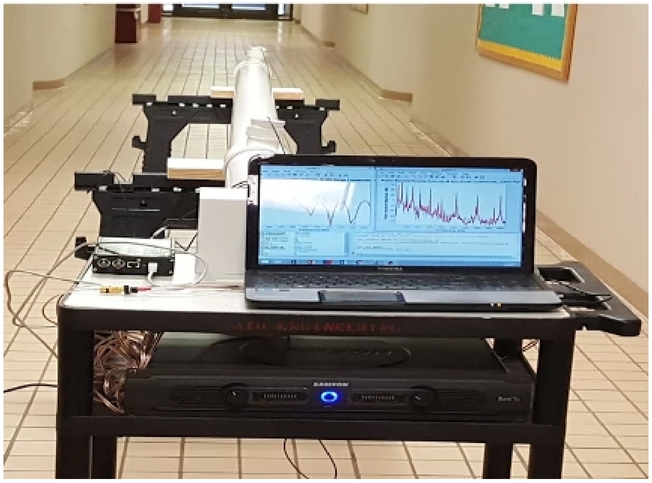

Figure 2: Test Setup.

Results

The acquired data from both microphones is analyzed to observe any changes in the pipe's frequency response due to presence of a crack. An important analysis technique to observe variation in the power present in a signal per unit frequency is the power spectral density (PSD) estimate via Welch's method given in dB/Hz. The raw PSD of the mid-frequency band signal acquired from output microphones in both clean and cracked pipes is plotted in Fig. 3. The analysis reveals that acoustic signal at 1.25 kHz is attenuated by over 3 dB in cracked pipe (from -34.7 dB to -37.8 dB). Signal loss of over 2 dB is also observed at 400 Hz. Minor losses (about 1 dB) are also observed at 500 Hz and 2.0 kHz. Minor signal gain in cracked pipe was observed at 315 Hz and 800 Hz. This is attributed to pipe resonances which occur at multiples of 35 Hz.

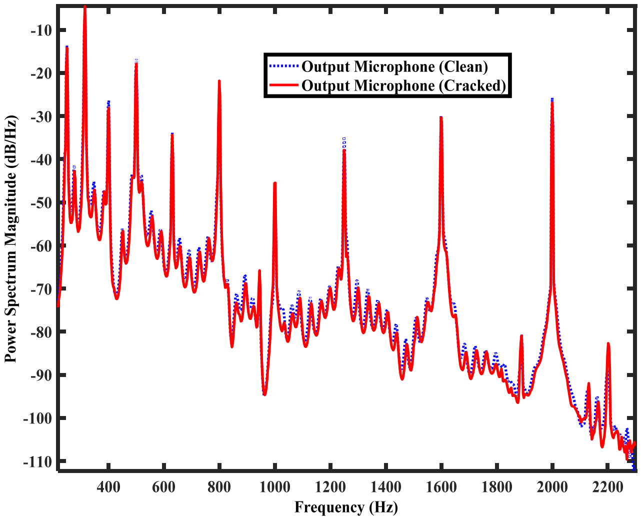

Figure 3: Raw Power Spectral Density via Welch's Method – Mid-Range Frequencies (Pipe with no cracks).

In audio signal analysis, spectrogram is an effective technique that provides visual representation of power in signal frequencies with time. Figs. 4 and 5 give spectrogram of data from output microphones in both clean and cracked pipes. Significant signal loss is observed at 1.25 kHz in cracked pipe that confirms results of PSD analysis. Pipes were also tested with audio signals other than discrete tones detailed in this paper. These included linear chirp, direct sequence spread spectrum and pink noise. The results from those tests are not presented here due to paucity of space.

It was observed during the tests that frequencies in low frequency band (especially less than 100 Hz) are not produced efficiently by the Tang Band speaker. These frequencies, therefore, will not be used in future testing.

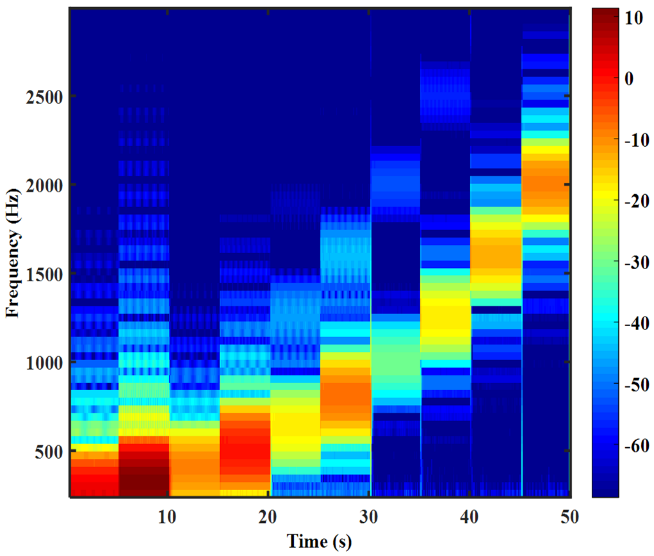

Figure 4: Spectrogram plot – Mid-Range Frequencies (Clean Pipe).

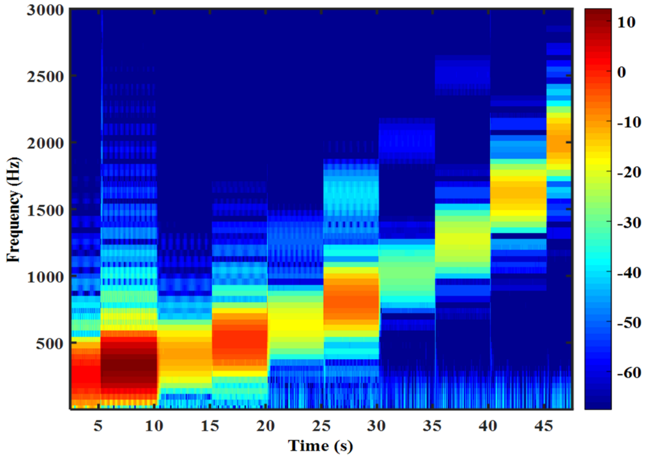

Figure 4: Raw Power Spectral Density via Welch's Method – Mid-Range Frequencies (Cracked Pipe).

Conclusion

The goal of this project was to develop an approach to monitor condition of pipes especially existence of cracks using acoustic signals. The motivation for this study has been drawn from successful use of acoustic signals to detect blockages in sewer pipes. Empirical data from extensive lab testing has enabled us to observe effect of cracks in pipes on acoustic signals at discrete frequencies. Significant signal losses were observed at 1.25 kHz and 400 Hz in a cracked pipe. Results from this study will be used to motivate and justify further testing both in laboratory and the field. The team will also use advanced techniques (such as wavelet transforms) to analyze empirical data collected during future tests. The results will enable the team to accurately predict the existence and extent of cracks and other defects in pipes.

Acknowledgements

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