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Low cost on-line non-invasive sewer flow monitoring

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Abstract A novel acoustic sensor has been developed, capable of remotely monitoring the free surface 'fingerprint' of shallow flows. Temporal and spatial properties of this pattern are shown to contain information regarding the nature of the flow itself. The remote measurement can thereby be used to infer the bulk flow properties such as depth, velocity, and the hydraulic roughness of the pipe. The instrument is non-invasive and is also low cost, low maintenance, and low power. Such a device will allow for widespread monitoring of flow conditions in drainage networks, enabling pro-active maintenance and reliable real time control.
Keywords Flow monitor; water surface; waves; ultrasonic; phase.

INTRODUCTION

Monitoring wastewater flows

Urban drainage infrastructure is becoming more frequently overloaded by heavy flows. Rising urbanization bypasses the natural infiltration processes, while a growing population demands greater capacity from our sewer systems. Ashley et al. (2005) examined four existing UK urban catchments and estimated that between 100-250% extra properties could be flooded under different planning scenarios by 2080. Some studies now propose that sewer network performance should be enhanced using data from networks of monitors (e.g. Bijnen et al., 2012), and monitoring is identified as a primary principal of the European Commission Urban Waste Water Directive (1991). Flow properties and conduit conditions must be monitored to minimise failures with proactive maintenance and potentially real-time control, however the best technologies at present are too costly for mass deployment, and are invasive, requiring regular costly maintenance. It is the aim of this paper to examine a potential new method of hydraulic measurement that may offer the potential for real time low cost flow monitoring.

Flowing water exhibits a unique surface pattern driven by flow turbulence (Tamburrino and Gulliver, 2002). This pattern appears to be a function of the underlying flow properties (Nichols et al., 2010). In this work, a low cost technique is developed for monitoring water surface fluctuations very accurately. Using this principle, an airborne acoustic sensor is developed which is capable of remotely characterizing the temporal and spatial properties of the free surface pattern on shallow flows (Nichols & Horoshenkov, 2012). Using such a method, it is possible to obtain a velocity measurement by tracking the free surface pattern, and a depth measurement by standard time-of-flight (TOF), and to hence estimate flow rate.

Sensing water surfaces

In order to accurately measure the temporal and spatial properties of a fluctuating free surface, time series of surface elevations are required, simultaneously, from a number of locations on the free surface. In the laboratory this is usually achieved through an array of wave probes (Denissenko et al, 2007). The most common wave probes function through either electrical conductance or capacitance. Both of these techniques suffer from two inherent disadvantages. Firstly, they require a calibration to be performed, and the data may only be trusted while the conditions (e.g. salinity, temperature) under which the calibration was obtained are upheld, meaning these types of device are usually used only under laboratory conditions. Secondly, they must penetrate the flow surface in order to obtain a reading. There are many scenarios where this type of invasive technology is impractical, most notably flows containing suspended particles or debris which will accumulate on the instrument and cause failure. Wastewater flows are a good example of this.

A number of attempts have been made to quantify local surface fluctuations optically. Some researchers investigate the use of infra-red and laser displacement techniques (Daida, 1995; Takamasa and Hazuku, 2000), while others use stereoscopic imaging to monitor the vertical location of one or more points of light projected onto the surface (Tsubaki and Fujita, 2005). These techniques however are difficult to implement for real flows since water surfaces are poor reflectors of light (most energy passes through the surface). In the laboratory this can be improved by adding a colorant to the water, but this is not practical for wastewater flows.

In order to remotely characterise water surface patterns accurately a new technology is required which is less invasive than electrically based techniques and more robust for field applications than optical methods. One attractive option is the use of acoustic instrumentation, since water surfaces behave acoustically hard and therefore reflect acoustic signals well.

Acoustic techniques are well studied in the context of monitoring the mean location of fluid interfaces. The most commonly used technique is a basic time-of-flight (TOF) measurement, whereby an acoustic pulse is emitted, and reflects back from an area of the surface. The time between emission and reception of the reflection indicates the average distance to the surface, based on an assumed or independently measured local sound speed (Lagergren, 2012). Some technologies project acoustic energy toward the surface and then analyse the phase of the received signal in order to estimate the mean surface level (Redding, 1983). These techniques measure the mean surface position, but they do not detect local water surface fluctuations.

This work investigates a method of very accurately measuring the dynamic fluctuations of a water surface by analysis of the temporal variation of a reflected (forward scattered) acoustic wave. A continuous wave is used, in order to output a time series of fluctuation data. The source is operated at an ultrasonic frequency to provide a more directional acoustic signal, minimising unwanted multiple reflections, and approximating more closely to measuring at a point on the surface rather than averaging over an area.

MEASUREMENT METHODS & SENSOR DEVELOPMENT

Measuring surface fluctuations acoustically

Consider a monochromatic ultrasonic wave reflected specularly from an acoustically hard surface toward a microphone some distance away (Figure 1). The received signal will have a difference in phase when compared to the transmitted signal, due to the time taken for the acoustic wave to travel from source to receiver. When the reflecting boundary is stationary this phase difference is constant. If the surface is displaced vertically, the phase difference is altered due to the change in path-length. A fluctuating surface will thereby generate a fluctuating phase difference. A key limitation is that the acoustic signal actually acts over a small area, and the dominant wavelength of the rough surface must not be smaller than the diameter of this area, which may be determined by Fresnel theory (Nocke, 2000).

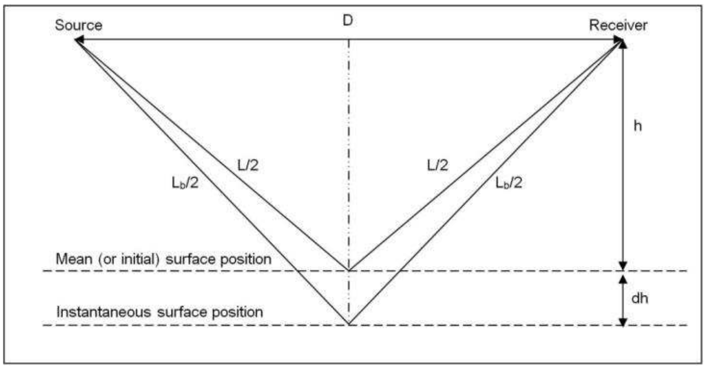

Figure 1: Source-receiver geometry.

Relative positions of source and receiver are known, so phase measurements may be used to calculate the fluctuation of the flow surface in mm at the point of specular reflection.

To demonstrate the theory, a 45 kHz source and a receiver were set up in a 12 m long, 0.46 m wide tilting flume (Figure 2). The substrate used was washed river gravel with a near normal distribution, a mean grain size of 4.5 mm, and a standard deviation of 1.7 mm. The bed was scraped flat with no appreciable bedforms. Initially, a range of 7 steady flows were established at a gradient of 0.004 in order to generate surface fluctuations of varying scale and spectral composition. The flow rate was increased from 5 to 45 l/s causing the peak wave height to increase from 1.5 to 3.6mm. Flow conditions were selected to ensure a non-mobile bed and sub-critical flows. A downstream control was adjusted so as to ensure uniform flow conditions at the measurement location. A conductive wave probe was installed at the point of specular acoustic reflection in order to assess the accuracy of the acoustic technique.

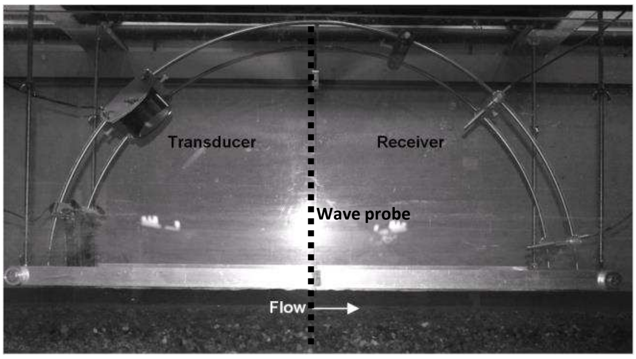

Figure 2: Laboratory setup.

The phase data is compared against the wave probe data for 3 of these regimes in Figure 3.

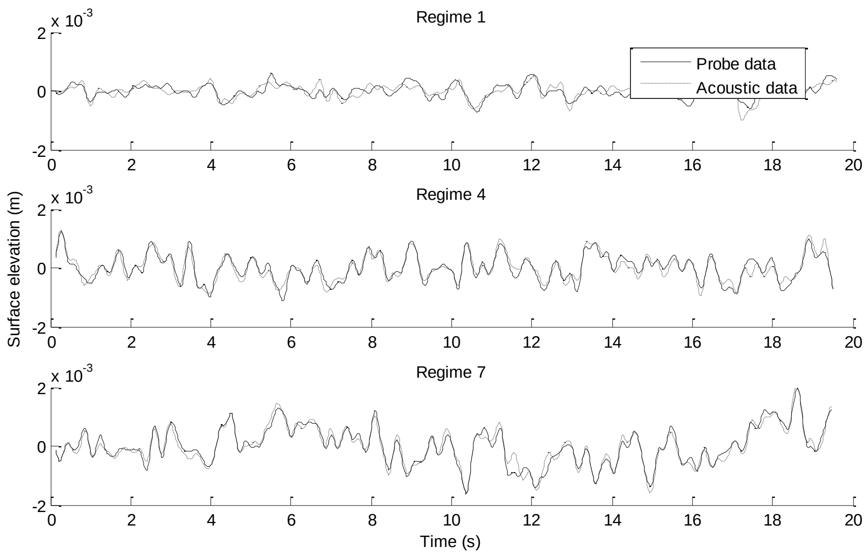

Figure 3: Acoustically measured free surface fluctuations.

It was found that the error relative to wave height is below 4% when the mean absolute local water surface gradient is below 0.025 and the wave height is above 4% of the acoustic wavelength.

Surface velocity and mean depth measurement

Multiple acoustic receivers allow for fluctuation measurements to be synchronously recorded at several spatially distributed locations on the flow surface (Figure 4).

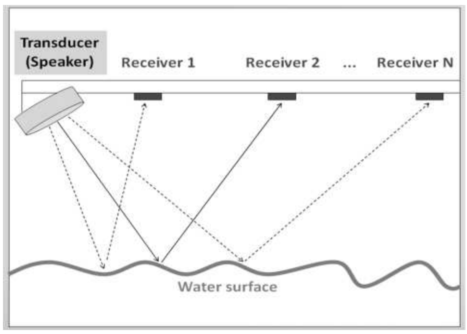

Figure 4: Generic schematic of spatiotemporal wave monitor design.

Since each receiver has a unique point of specular reflection, and the location of these points is known based on the location of the individual receivers, the surface can be monitored as it passes each microphone, and its velocity can be calculated using cross-correlation. Figure 5 shows the surface pattern recorded at two locations in an arbitrary flow regime. The clear temporal lag reveals the surface flow velocity. Any debris in the flow would be detected at both locations so would not corrupt the measurement. Mean flow depth may be measured using a standard time-of-flight technique whereby a pulse is emitted from the transducer, reflected from the flow surface, and received at each microphone. The time between emission and reception allows the location of the flow surface to be determined relative to the sensor.

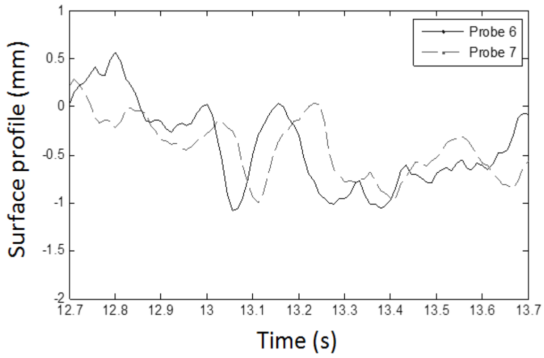

Figure 5: Spatially separated surface fluctuations.

Sensor design

The prototype reported here is designed for 150mm diameter pipes (Figure 6). It uses an array of 7 microphones positioned 135, 154, 176, 200, 227, 259, and 297 mm from the transducer respectively. This enables the acquisition of data for any potential water level, and allows for averaging of the depth and velocity readings from different receivers or receiver pairs.

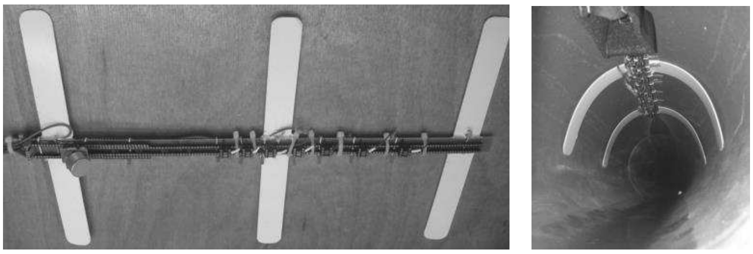

Figure 6: Prototype designed for 150mm diameter sewer pipes.

RESULTS & DISCUSSION

Field testing in a 150mm diameter foul sewer

The sensor was installed in a 150mm foul sewer shown in Figure 7. Velocity and depth were acoustically estimated using the techniques described above. Reference measurements of depth and velocity were recorded using a point gauge and a saline tracer respectively.

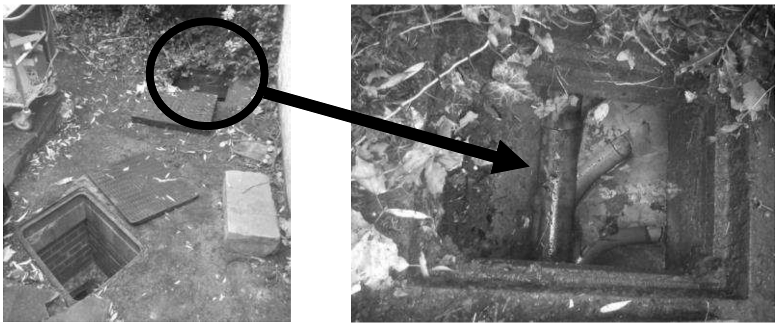

Figure 7: Field installation site.

Three flow regimes were examined, with the results given in Table 1. It can be seen that the maximum errors for depth and velocity were 5% and 8% respectively.

Table 1: Error in acoustically measured mean velocity and flow depth.

Flow Regime	Point Gauge (mm)	Acoustic Depth (mm)	Depth Error (%)	Mean Velocity (m/s)	Acoustic Velocity (m/s)	Velocity Error (%)
1	15	15.8	5	0.58	0.59	2
2	16	15.7	2	0.59	0.54	8
3	9	8.7	3	0.29	0.27	7

The acoustically measured mean velocities were estimated from the acoustically measured surface velocities by assuming a standard velocity profile of the form $U/U_\infty = [0.2]^{\frac{1}{6}}$, where U is the mean velocity and U_∞ is the free surface velocity. 0.2 represents the fraction of the flow depth at which the mean velocity occurs, found experimentally for this pipe. This profile may be assumed for similar pipes, though direct measurement may provide more accurate profiles.

Flow rates were then calculated using the acoustic and reference measurements of velocity and depth. The results, and the associated errors, are given in Table 2.

Table 2: Acoustically estimated flow rate accuracy.

Regime	Measured Flow rate (l/s)	Acoustic Flow rate (l/s)	Error (%)
1	0.53	0.59	10%
2	0.60	0.53	11%
3	0.13	0.11	11%

The flow rate measurement is accurate to within ±11%. The Environment Agency specifies that flow monitors must be accurate to within ±8% in order to achieve MCERT certification (Environment Agency, 2013). It is expected that with further refinement and development of signal processing techniques, the device presented here will perform within those guidelines.

Deciphering information hidden in the surface pattern

During the laboratory tests described previously, it can be observed that the roughness pattern on shallow flow evolves gradually as it travels downstream. This evolution in surface pattern was measured in the laboratory using an array of wave probes, but in future may be quantified from surface fluctuation data obtained at multiple locations on a flow surface using the acoustic device. The dependence of the correlation upon the spatial separation follows an oscillatory relationship, known as the spatial correlation function (SCF). Examples of this for the same three arbitrary regimes in Figure 3 are shown in Figure 8.

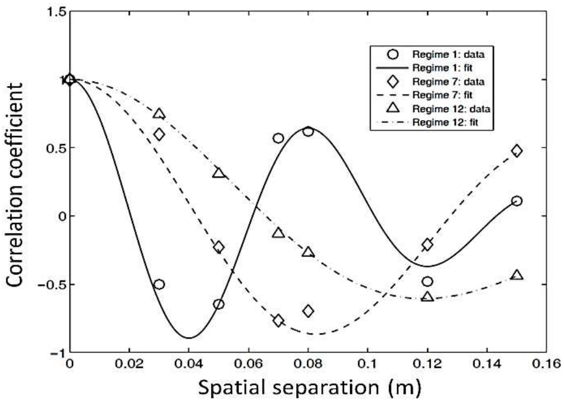

Figure 8: Spatial correlation functions.

This spatial correlation function may be approximated by $W(\rho) = e^{-\frac{\rho^2}{\sigma_w^2}} \cos\left(\frac{2\pi}{L_0}\rho\right)$, where ρ is the spatial lag, σ_w the correlation radius and L_0 the characteristic spatial period. Also measurable is the root-mean-square (RMS) wave height. Data was collected for an ensemble of regimes established in the flume at gradients from 0.001 to 0.004. A SCF was calculated for each regime. Relationships to bulk hydraulic properties are shown in Figure 9.

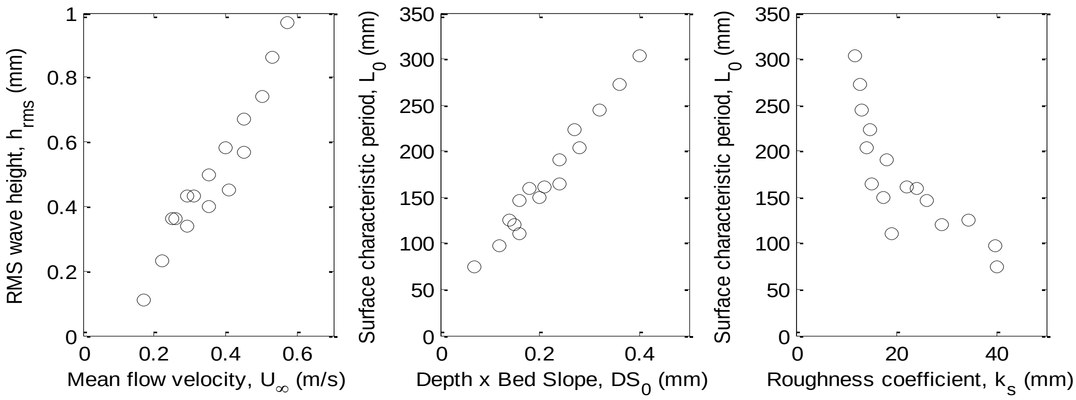

Figure 9: Relationships between free surface roughness and bulk flow properties.

The physical nature of the surface roughness appears to contain information about the flow. Not only may it provide independent measures of velocity and depth, but it may also infer hydraulic roughness of the pipe and thereby provide data on its current condition.

Comparison with state-of-the-art

The proposed ‘forward scatter acoustic flow monitor’ system is compared against existing technologies in Table 3. It can be seen that a suitably developed version of this system may hold several advantages in terms of minimising costs and avoiding the limitations of existing sensors, while potentially providing more detailed measurement of the flow conditions, not limited to solely the flow velocity and flow depth.

Table 3: Comparison with existing flow monitoring technologies.

Technology	Est. Price	Est. Error	Advantages	Disadvantages
Acoustic Doppler flow profiler	£20k	Vel: ±0.5% Depth: ±0.5%	High accuracy. Measures velocity profile.	Contact device. Expensive. Min. depth ~50mm.
Radar-based flow monitor	£12k-15k	Vel: ±0.5%±0.02m/s Depth: ±5.0%	Non-contact.	Requires rough water surface. Average velocity estimated from surface velocity.
Laser-based flow monitor	£8.5k	Vel: ±0.5% Depth: ±5.0%	Non-contact. Measures to 11% below surface.	Average velocity estimated from peak velocity. Requires particles in flow to reflect signal.
Doppler area velocity flow monitor	£3.5k	Vel: ±2.0% Depth: ±1.0%	Measures average velocity. Relatively low cost.	Contact device. Min. depth ~25mm. Requires particles in flow to reflect signal.
Forward scatter acoustic flow monitor	~£1k	Vel: ±8.0% Depth: ±5.0%	Non-contact. Low cost. Low power. May infer hydraulic roughness, bed slope, etc.	Average velocity estimated from surface velocity. Requires slight surface pattern.

CONCLUSIONS

A sensor has been developed which makes use of the turbulent nature of depth limited flows by simultaneously measuring the surface pattern at numerous locations, and using this data to measure depth, velocity and hence flow rate. Field testing showed that depth, velocity and flow rate could be measured to within 5%, 8%, and 11% respectively. Laboratory tests show that it may also be possible to measure hydraulic roughness, physical bed roughness and sediment transport properties. The sensor is non-invasive and as such presents a device that could operate with lower maintenance and thus lower cost than standard pipe-bottom mounted monitors. The use of forward scattered signals means that power consumption is lower than that of traditional Doppler backscatter devices (and thus battery life is longer). The ultrasonic components are low cost and could be made to withstand surcharged conditions. These advantages allow the potential for deploying such technology widely throughout the sewer network allowing a data driven approach to estimating sewer condition to be possible.

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