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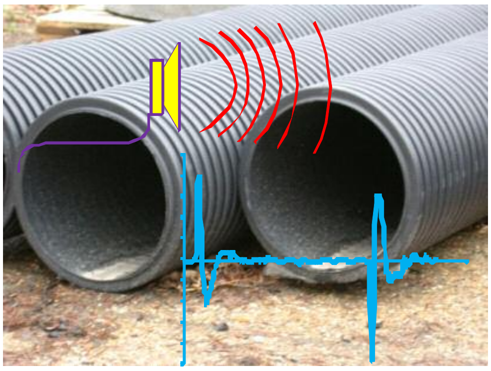

Non-invasive techniques to assess drains

by M Harrington and J Iaquinta

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Executive summary

Failures on road networks can occur because the drainage system is not able to cope with the large volume of water that suddenly has to be evacuated during periods of heavy rainfall or snow. It is therefore essential to collate accurate "*data about the location and condition of highway drainage assets in order to plan ordered and cost effective maintenance"* so that drains remain fully operational at all times.

However, on motorways and trunk roads, drain inspections are only carried out once in every decade, under traffic management, with cameras or mandrels which have to be introduced and manoeuvred in the pipe. These are expensive, time consuming and subject to errors. Although this inspection regime may be suitable to identify major structural failures it is not appropriate to detect flaws that could have been contained and treated early to avoid further damage and maintain the serviceability of the drainage.

Hence, there is scope to develop a rapid and robust approach to detect drains likely to be defective or poorly performing, without the constraints and limitations of existing techniques. This would make it possible to carry out regular assessment for preventive rather than reactive maintenance, such that further detailed inspections could be concentrated on only sections highlighted as having a high probability of being faulty.

This project has explored several non-invasive techniques to identify the most suitable approach. The fundamental idea was to take advantage of certain features (cross-section, internal wall roughness, discontinuities, etc.) that drains exhibit, and how they interact with air "packets" and acoustic or light waves. Therefore, by providing an appropriate stimulus and analysing the response of the pipe it would be possible to determine when a drain is, or is not, in poor condition.

The review concluded that, considering the difficulties highlighted for the use of light and air packets, acoustic methods would be more successful and, among these, the most promising was thought to be acoustic pulse reflectometry. Unlike the light or air packet approaches, this method uses off-the-shelf components to emit, receive and process the signal.

Experiments were carried out on a test rig built using materials comparable to those found on the Highways Agency drainage network. A series of 6m long and 300mm diameter plastic pipes were assembled above ground and indoors, connected together by push-fit joints and rubber ring seals, to form a 30 metre pipeline. Two configurations were considered: one in which the exit of the pipe was left open and one in which it was sealed. It was shown that the method was able to gain, in a few seconds, information about the condition at the far end of the pipe, even without line-of-sight.

Although the acoustic technique identified was the most promising of those investigated, more research is needed to answer some of the questions raised (actual implementation of the method, interpretation of the measurements, etc.) and to validate the approach.

Abstract

Often, failures on the motorway and trunk road networks resulting from heavy rainfall occur because drains are not able to cope with the large volume of water they have to evacuate. Currently the assessment of these drains is undertaken every 10 years using visual (Close Circuit Tele-Vision) or manual (mandrel) techniques. This inspection regime may be suitable to identify structural failures but is not appropriate to detect problems (such as blockages or build-up of debris) requiring immediate treatment. The objective of the project was therefore to identify a potentially efficient, cost effective and simple approach that would allow the detection of defective or poorly performing drains without the limitations of the "traditional" methods. Several techniques based in particular on the reflection and/or transmission of air "packets", sound and light were considered in order to determine which approach was most likely to deliver a successful outcome.

1 Introduction

The last few years have seen an increase in the frequency and intensity of heavy rainfall and snow events. Such incidents have had quite large impacts on the transport sectors. Failures on the road network have occurred because the drainage systems were not able to cope with the large volume of water they suddenly had to evacuate. This emphasised the need to ensure that drainage systems are effective at all times, in order to minimize flooding and traffic disruption.

Currently on the motorway and trunk road network the assessment of longitudinal piped drains more than 5m long is undertaken approximately every 10 years. Such an assessment regime is inappropriate for the detection of problems requiring immediate treatment such as blockages or the build-up of debris. At present inspections are made visually (Close Circuit Tele-Vision) or manually (mandrel), with equipment which has to be introduced into the drain. This process is time consuming and expensive. Also, the drains are not necessarily laid in perfectly straight lines (either horizontally or vertically) which affects line-of-sight methods, meaning that devices such as video cameras have to be manoeuvred along the pipe.

It would be beneficial to have a reliable and cost effective approach to detect defective and/or poorly performing drains with minimal intrusion and without the constraints and limitations of “traditional” techniques. This would make possible an evolution towards more regular and less disruptive drainage assessments, and preventive rather than reactive maintenance.

In this research several non-invasive techniques have been considered from a theoretical point of view in order to propose which is most likely to provide successful equipment to assess piped drains, in a more efficient manner than current techniques.

This report starts with an introduction to the drainage networks and current assessment procedure. Envisaged alternative inspection methods are described and their advantages and disadvantages discussed. The most promising of these techniques is then presented in more detail with results of initial experiments carried out to determine its potential.

2 Current situation

This work concentrates on the typical drainage network installed on England’s 7,754km of motorways and trunk roads.

2.1 The drainage network

In general, the drainage network is designed such that surface water is directed into one or more plain pipes, which usually have a circular cross-section (see Figure 1), running parallel to the main carriageway. There are also so-called “filter drains” made with perforated pipes, but these were out of the scope of the present work.

Figure 1: Example of plain plastic pipe used in this research.

On the main water carrying drainage system there are manholes located at intervals of about 100 to 150m. These manholes are commonly made from prefabricated concrete or plastic chambers with a cover and an aperture on top for access, and it is generally through these manholes that drain inspections are performed.

The network consists of a large variety of pipes of different diameters (up to about 1m), materials (concrete, clay, plastic, bricks, etc.), ages and condition. This research focused on 300mm diameter plastic pipes, chosen after consultation with the industry and practitioners who highlighted them as their preference for current construction works.

The plastic pipes come in short units, generally a few metres in length, and are joined together to form the longer sections terminated by manholes. In most cases watertight joints are used. A test is required on installation to ensure the tightness of the seals (however no such test seems to be carried out once the drain is in service).

2.2 Assessment procedure

2.2.1 At commissioning

The requirements of commissioning tests are outlined in the Manual of Contract Documents for Highway Works [1]. It states that the pipeline under test must be isolated using bungs to block off openings. Next, air is pumped into the pipeline until a stable predefined pressure level is reached. The section is then left for 5 minutes before the pressure is measured again. If the drop in pressure is greater than a predefined value, “rectification” work must be carried out. Part of this rectification work allows for the pipeline to be retested using a water-based method. The latter procedure is very similar to that implemented during the air test, but instead water that is pumped into the pipe until a stable pressure is achieved. If this subsequent test is passed, then no further work is required.

In addition to the leak tests, mandrels may also be used during the construction process to ensure a free flowing pipeline. Mandrels are designed to be specific sizes and shapes depending on the pipeline they are to be used in. They are pulled through a pipe and get jammed at points of construction defects. Their size and shape define the tolerances that a pipeline must meet. Too great a kink at a joint or deformation and the mandrel will not pass. One key issue with mandrels is their ability to only inspect the pipeline up to the point of the first defect. At which point they must be removed and the defect dealt with before the survey can continue. This can make the process very time consuming, and thus identifies another area for which an alternative inspection method might be beneficial, even at the time of commissioning.

2.2.2 In service

The assessment of the Highways Agency owned drainage network is undertaken on a ten year cycle, accordingly about 1/10th of drains are inspected each year. This inspection is extremely time consuming, requiring traffic management, and as such is very expensive.

The current assessment procedure requires the inspections to be carried out using Close Circuit Tele-Vision (CCTV), which must be introduced into the pipeline. The equipment is manoeuvred in the pipe using a tracked/wheeled device that remains tethered to the operators, located close to the entrance to the pipe. The camera requires lighting as well as pan and tilt capabilities. Such systems are used to inspect pipes up to 1800mm in diameter and must be capable of surveying up to 200m from the entrance [2].

As the device negotiates through the pipe the operator scans for features of interest. On encountering such a feature the equipment is used to make a closer inspection of the pipe, as well as to record the position of the feature. The location of features identified within the drain pipe must be recorded to an accuracy of ± 1% or 0.3m whichever is the greater [2]. The maximum linear speed of the camera is also specified, increasing with the diameter of the pipe. For drains of diameter 300mm and larger a maximum speed of 0.20m/s is defined [2]. At that speed the inspection of 150m of drain would take a minimum of 750s (12.5 minutes), highlighting the slowness of this method.

A range of features are reported in CCTV inspections which can be divided into three categories [2]. The first category comprises features related to the pipeline structure and includes cracks, fractures, deformations, breaks, collapses and defective repairs. The second category relates to the operation of the pipeline and covers roots growing into the pipeline, deposits and obstacles. The third category relates to the inventory of the pipeline and includes the position of another pipeline connected to the pipeline under inspection, short sections of repair and curvature of the pipeline that that does not take place at a joint.

2.3 Work under traffic management

Inspections of drains on the Highways Agency network require a vehicle and operators to work under traffic management. The guidance, issued by the Highways Agency for works on the hard shoulder states that, for any vehicle parked on or encroaching on the hard shoulder that stops for longer than 15 minutes, traffic management must be in operation [3]. England’s motorways and trunk roads are among the busiest in Europe, therefore such traffic management can be very disruptive for road users, tedious and extremely expensive to implement. For this reason, an approach able to carry out an assessment of a section of pipeline within the 15 minute time limit, and so not requiring heavy traffic management, would hugely simplify the routine inspection of the drainage network.

2.4 Features of interest

After having been carefully put in place and tested, the drains are sometimes damaged when other roadside equipment is added (e.g. perforation associated with the installation of crash barriers, signs or post, as shown on Figure 2a). The pipes also undergo inherent ageing with, for instance, the advent of cracks (Figure 2b), deformations of their cross-section (Figure 2c), growth of roots (Figure 2d) and deposition of materials or blockages (Figure 2e) which eventually translate into a decrease in the serviceability of the drain.

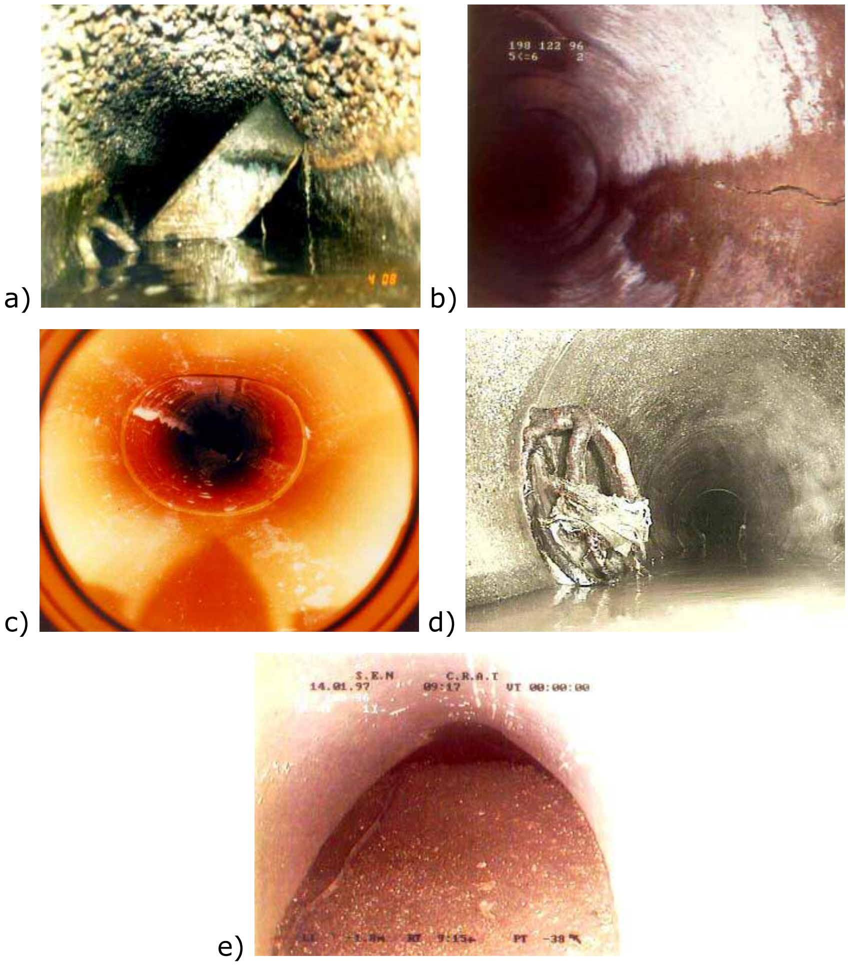

Figure 2: Examples of a) pole obstructing the cross-sectional area of the pipe, b) longitudinal crack visibly open in the pipe wall, c) deformation, d) roots growing into the pipeline and e) deposited material.

3 Alternative assessment procedure

3.1 Objective

This research aims to identify an approach to enable the quick and objective assessment of drains for obstructions, such as roots and deposits, affecting their serviceability. The technique would ideally need to work with access to only one end of the pipe to meet the requirements of current CCTV assessment work, and offer an operational range in the region of 100 to 150m. The technique would be expected to survey this length significantly faster than the current method (12.5 minutes).

A large range of different drains can be found on the network, therefore the plan was to fulfil the need of the most common type of pipe, which was found to be 300mm diameter plastic pipes, keeping in mind that there would be a need to apply the same approach to pipes potentially exhibiting a different diameter. It was also identified that sections of pipe could not be assumed to be straight and free from kinks at the joints or bends in individual units of pipe.

3.2 Considered approaches

Several approaches were identified for the non-invasive inspection of drain pipes, based on the use of air "packets", light and acoustic waves.

3.2.1 Light based techniques

Light line and laser-based profilometry are two systems which employ lasers to aid the inspection of pipes. Light line is used in conjunction with CCTV. The system is manoeuvred down the pipe, as is the case for standard CCTV, with the addition that a line of light is projected onto the wall of the pipe as it goes. The shape produced by the line of light is analysed from the CCTV images to judge the circumference of the pipe. If a deposit on the wall of the pipe is reached the line of light is distorted. This distortion can be analysed to determine the size of the deposit. Laser-based profilometry also requires the system to be manoeuvred down the pipe. In this case a laser is used to scan the circumference of the pipe. Using techniques such as time-of-flight and measurements of the reflectivity of the surface of the pipe an internal profile can be created.

For both these techniques it is necessary for the equipment to be manoeuvred through the pipe under test. This limits the speed at which a survey can be carried out, providing no improvement in speed over standard CCTV.

For a laser based approach to show speed improvements over CCTV a technique would need to be developed that did not require the equipment to be introduced into the pipe. As such, the laser would need to be shone into the pipe at one end with any reflections observed at the same end (i.e., as in Light Detection and Ranging) and/or transmissions observed at the far end (with shadows betraying the presence of blockages). Several key problems were identified.

The first problem is related to issues with line-of-sight - It would have been difficult to implement such an approach if it were not possible to get a clear line-of-sight from one end of the pipe to the other.

As discussed above, sections of pipe on the drainage network could not be assumed to be straight and free from kinks at the joints or bends in individual units of pipe. Such kinks and bends would produce an impenetrable barrier to light and prevent inspection further down the line.

The second issue identified was a continuation of the first one. In this case where the inspection of the full pipe was prevented as a result of features present in the pipe. For instance, a blockage close to the entrance of the pipe might hide a complete structural failure behind.

The third difficulty was due to refraction. It is common for pipes to contain a small quantity of standing water. This standing water would introduce a medium boundary and as such refraction of the light. Since it might not be possible to identify standing water in a pipe and therefore compensate for it, refraction might introduce positioning errors (Figure 3).

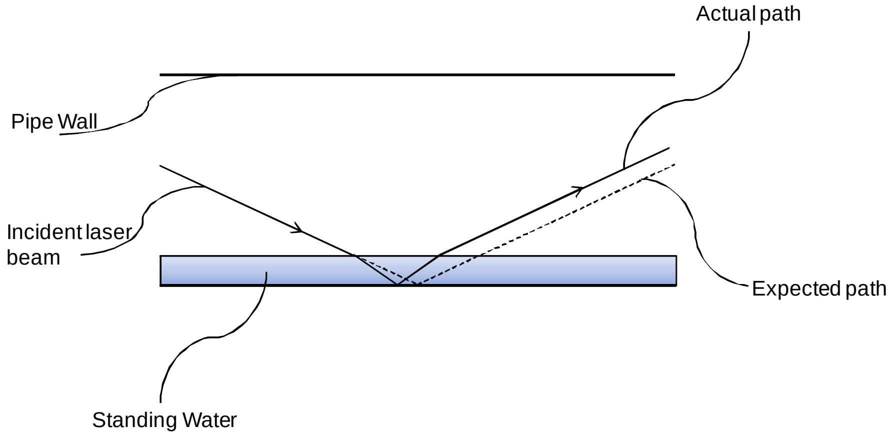

Figure 3: Light based method – refraction issues.

The final issue related to the introduction of diffraction. Here the shadow cast by an opaque obstruction/object would generate bright and dark regions, which would not have been expected by geometrical optics. This would make interpretation very difficult. The small angles of diffraction due to a laser beam interacting with a feature in the pipe would be accentuated over the length of the pipe (Figure 4).

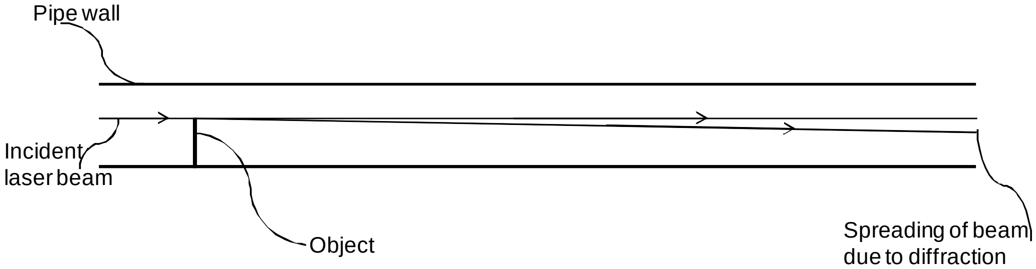

Figure 4: Light based method – diffraction issues.

3.2.2 Air "packet" techniques

This technique involves the injection of an air "packet" having a distinct shape, for instance a torus into a pipe with the intention of detecting possible changes in this shape. The areas of difficulty with such an approach were identified as being related to the generation, injection and sensing of the air packet during its trip, and also attenuation due to interaction with the internal wall of the pipe.

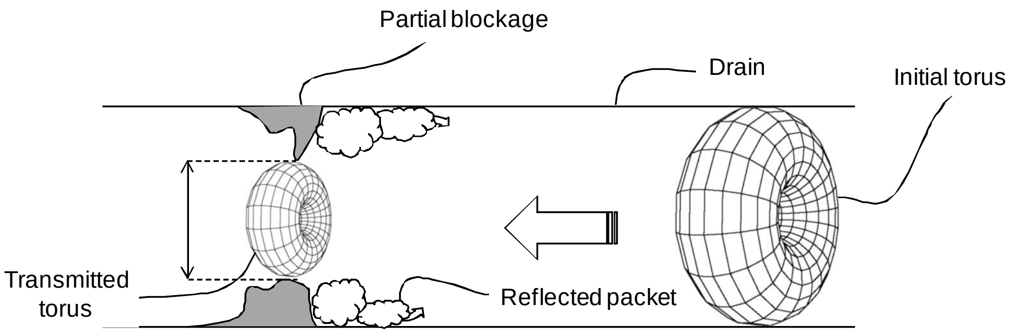

Figure 5: Example of a torus (as could be created with an air bazooka) sent in the drain and interacting with deposited material.

Assuming that the air packet is physically able to travel through the entire length of the drain, at its simplest the approach is considered to be an all-or-nothing inspection method, to identify pipes in need of further investigation based on the level of transmission.

To obtain more detail about the condition of the pipe, it would have been necessary to carry out a closer evaluation of the transmitted and/or reflected air packets, making comparisons with the original characteristics (in terms of their shape, nature, velocity, etc.). In the end it was concluded that such a characterization would be extremely difficult. Air packet shapes are complex and become only more so from the interaction with features of the pipe. Possible techniques to make measurements would involve the use of high speed cameras to watch for disturbances in smoke, or multiple pressure sensors. In addition, for such an approach to work it would have been necessary to create air packets that completely filled the cross-section of the pipe, otherwise detail would be lost about the condition of the volume not included in the path of the air packet.

Attenuation was found to be another issue for the air packet design. Air packets would in general be highly attenuated by obstacles and discontinuities in the pipes, as well as surface roughness of the internal walls. It was therefore thought that creating an air packet able to propagate successfully through a pipe would be challenging.

3.2.3 Acoustic techniques

Many applications make use of acoustics for the inspections of materials and systems, and these kinds of technique can also be used for the inspection of drainage pipelines. The transfer of liquids and gases, such as natural gas networks, ventilation systems, oil pipelines and water cooling systems, deals with similar scenarios. Medicine also uses acoustic techniques for the assessment of inaccessible parts of the human/animal body, including blood vessels and airways. None Destructive Testing (NDT) is extensively used in manufacturing to provide quality assurance, and deals with many of the same issues faced by the acoustic inspection of drains. The following sections summarise the related techniques and discuss how they helped to focus this research.

3.2.3.1 Leak noise

Leak noise "correlators" are commonly used in pressurised systems. Such devices make use of the acoustic signals created by leaks to pinpoint their locations. The signals are recorded using multiple microphones placed around a pipe network. With knowledge of the locations of the microphones it is possible to use cross-correlation to locate the source of leak noises detected. This makes for a simple but effective method of detecting this type of flaw in pipes. However it was not seen how it could be applied to the detection of blockages. If a noise could be associated with blockages this method could very well be adapted. However, if such a noise was only present under pressure it would inevitably be time consuming to implement in an unpressurised system.

3.2.3.2 Ultrasonic inspection

Ultrasonic inspection is extensively used in NDT for the inspection of solid material, flaw detection, dimensional measurements, etc. In standard ultrasound, such as that used in medicine to perform scans during pregnancy, an ultrasound wave is emitted into the object to be scanned and any reflections measured. Reflections of the emitted wave occur at interfaces and discontinuities within the object, and as such provide information about its condition.

Using this technique gas and petroleum companies routinely inspect their pipelines for corrosion and defects with sophisticated pieces of kit known as "pigs" (Figure 6). These pigs are intelligent robotic devices that are propelled down pipelines to evaluate the pipe interior, test its thickness and roundness, and detect other defects that may either impede the flow of gas or pose potential safety risk for the operation of the pipeline. Sending a pig down a pipeline is fittingly known as "pigging" the pipeline.

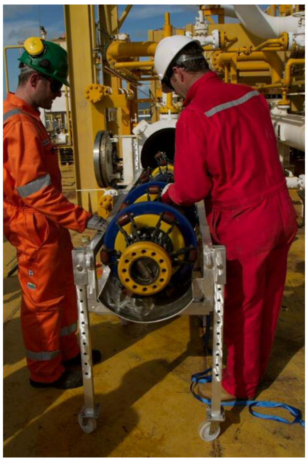

Figure 6: Example of pig for specialist application [from http://www.pipeline-pigging.com with permission from S Hutcheson, Pipeline Pigging Technology Limited].

Standard ultrasound however, can only inspect a short length of a pipeline at a time. As such, the pipeline must be scanned bit by bit. This can be done from either inside the pipe, as in the case of pigging, or from the outside of the pipe, if such access is available. In the case of drainage pipes, access to the exterior of the pipe is not possible, and access to the interior imposes speed constraints similar to those of CCTV. As such, standard ultrasound would be unlikely to show any speed improvements over CCTV.

Ultrasound guided wave inspection (Figure 7) takes advantage of the ability to propagate ultrasonic waves between two surfaces. As such, it has the capability of accessing longer lengths of pipe from a single measurement. As with standard ultrasound, as the waves travel through the object they interact with interfaces and discontinuities. The key to a successful inspection of drainage pipes is dependent on the levels of attenuation of the ultrasound waves. This is of particular concern for buried pipes due to the close acoustic impedance of the surrounding earth compared with that of air. Demma, Alleyne and Pavlakovic [4] examined the use of ultrasound guided waves to inspect buried pipelines. They were specifically looking at the detection of corrosion in metallic pipes, characterised by a reduction in the cross-sectional area of the pipe wall. Defects as small as a 1-2% change in cross-sectional area were distinguishable. The researchers were able to make inspections up to 100m on either side of the transducer, for a pipe in generally good condition and with a low density of features (such as welds, vents, valves, etc.). However, this range was substantially reduced to approximately 20 metres for a pipeline with heavy corrosion over its length. The range was reduced further still when conditions were such that attenuation, caused by contact between the pipe wall and surrounding earth, was at a peak, with ranges as small as 5m achieved.

This research showed promise. However, it suggested high attenuation could be expected in the case of non-ideal conditions. As a result, ultrasound guided waves are unlikely to be able to achieve the desired range of 100 to 150m required for this application.

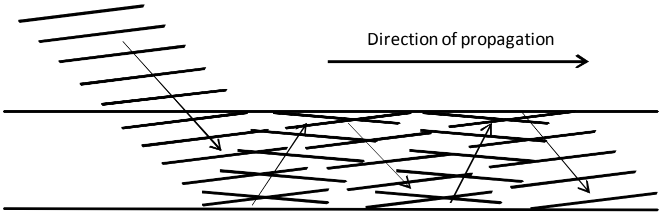

Figure 7: Ultrasonic wave guided.

3.2.3.3 Resonance and anti-resonance frequency shifts

The resonance/anti-resonance acoustic frequencies are well known properties of pipes. One form of inspection investigates shifts in these frequencies to detect blockages and leaks. Measurements of the resonant and anti-resonant frequencies of a pipe have been utilised in work by De Salis and Oldham [5]. Through calculations of shifts in these frequencies, compared with those for a clear pipe, it was possible to identify the location of blockages. De Salis and Oldham's research built upon work by Wu and Frickle [6] which in turn led on from work by Antonopoulos-Domis [7] examining blockage detection in nuclear reactor cooling systems. It improved on the practicality of the approach, by removing the need for two measurements with different boundary conditions to be made. Experiments were carried out on a 4m long duct of 0.2m diameter, and showed promise for the detection of blockages in pipes. In later work the technique was "applied successfully to the location and sizing of holes in the duct wall of circular ducts". [8]

This technique showed great promise. However, with less research into its capabilities and successful examples of applications it was not choosen in this work in favour of a more established acoustic technique involving the input impedance and Input Impulse Response (IIR), described in the following section.

3.2.3.4 Input impedance and Input Impulse Response

Measurements of the input impedance and the input impulse response have been used in medical applications as well as in the characterising of musical instruments. One such application is for use in medicine and the inspection of the nasal passage. "*Over the past decade acoustic rhinometry has become a well established method in rhinological research and practice*." Rhinoscan is an example of a commercial product exploiting this principle: "*in a matter of seconds, it measures the cross-sectional area and volume, and provides a two dimensional graphic display of the degree and location of constrictions and expansions*" [10].

The input impedance is defined as the ratio of the sound pressure to the volume velocity (which is the product of the particle velocity and surface area) at a given frequency. Once determined at each frequency (i.e., in the frequency domain) the impedance curve uniquely characterises the object under study. It is closely related to the IIR, a time domain parameter that can be calculated from the impedance by Fourier transform (it is actually defined as the real part of the inverse Fourier transform of the reflection coefficient derived from the acoustic impedance). The IIR is the response of an object to an acoustic impulse. The response is caused by acoustic impedance changes causing partial reflection and transmission as the acoustic wave propagates along the object.

Historically the input impedance has been measured directly in the frequency domain, using methods such as Two Microphone Four Calibration (TMFC) and Brass Instrument Analysis System (BIAS). Though some researchers have attempted to improve upon the original procedure for measuring the input impedance, in general "*it was first necessary to measure the volume flow rate. The pressure was then measured at the entrance to the instrument and divided by the volume flow rate to give the input impedance*…." and "*The method yielded excellent results but was very time-consuming, requiring the initial volume flow rate measurement and then a pressure measurement at each frequency of interest*" [9]. For these reasons the measurement of the input impulse response in the time domain has become popular through Acoustic Pulse Reflectometry (APR).

Acoustic pulse reflectometry has the advantage that it only requires the measurement of the pressure and therefore is much easier to implement than measurements of the input impedance. This is the technique that was chosen to go forward in this research, and is discussed in more detail in the following section.

3.3 Conclusion

Considering the difficulties highlighted for the use of light and the use of air packets it was deemed that acoustic methods showed the greatest promise. Unlike the air packet approach, an acoustic method can utilise standard components, e.g. a microphone and acoustic source. In addition, acoustic waves should be easier to propagate successfully through the pipe and line-of-sight should be unlikely to cause major problems.

4 Acoustic Pulse Reflectometry

Acoustic Pulse Reflectometry was originally developed to study the density profile of the Earth's crust. In this application an approximate acoustic impulse was injected into the surface and the complex response due to reflections at impedance changes between the layers was recorded. Extracting the boundary reflection coefficients from the response was not trivial, and was first achieved by Ware and Aki [11]. It was subsequently found that the technique could be applied to air filled ducts, to make measurements of airway dimensions [12]. Jackson *et al*. modelled the airway as a series of discontinuously joined cylindrical segments of equal lengths but differing cross-sectional areas (and, hence, differing impedances). *"The problem of measuring airway dimensions was thus reduced to one of finding the areas of the individual segments (an analogous problem to that of determining the impedances of the individual layers of rock in the earth's crust)*" [9]. More recently APR has been used in the characterisation of musical wind instruments. Figure 8 outlines the approach taken by Sharp [9]. A signal was created by a computer, passed through a digital to analogue converter and amplified before being sent to a loudspeaker. The acoustic signal produced by the loudspeaker propagated through a source tube coupled to the object under test. A microphone placed in the source tube a distance ℓ_1 from the loudspeaker and ℓ_2 from the object then listened to the response of the object. The measured response was amplified, passed through an analogue to digital convert and fed to a computer for processing.

Sharp discussed how it was necessary to introduce a source tube due to the finite width of the excitation pulse and reflections introduced by the loudspeaker. The length ℓ_2 is *"necessary to ensure that the input pulse has fully passed the microphone before the first of the returning object reflections reaches it"* [9]. In the ideal case of an impulse ℓ_2=0m. Reflections from the object then emerge from the object into the source tube. They pass the microphone and are subsequently reflected by the loudspeaker. The length ℓ_1 is "*necessary to separate the object reflections from these source reflections*" [9], which requires $\ell_1 \geq \ell_3$.

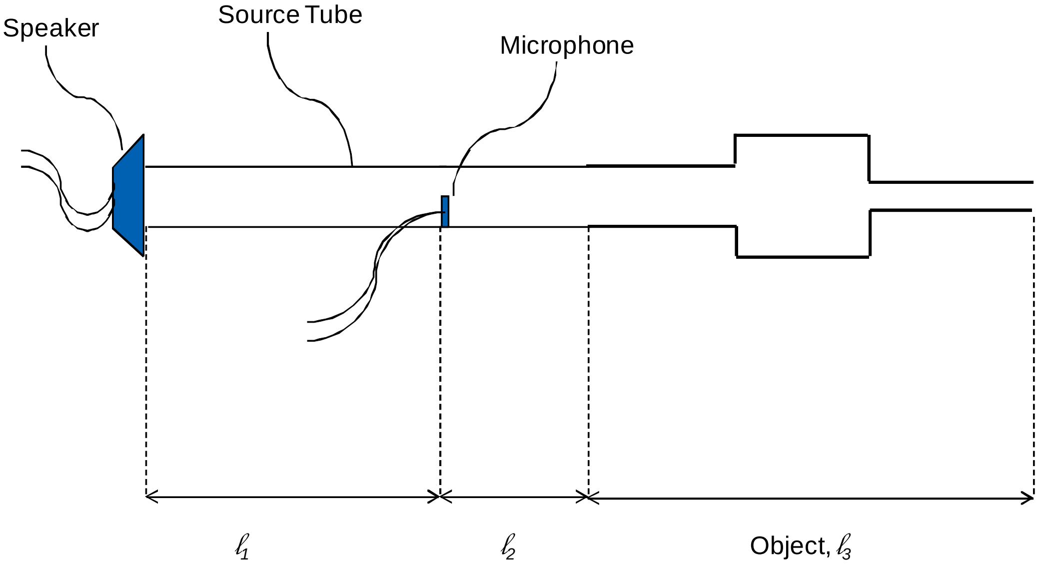

Figure 8: Schematic diagram of a pulse reflectometer.

In the ideal case an impulse is used as the stimulus for the system under inspection. In practice it is not possible to recreate a perfect impulse (i.e., Dirac's delta function), and hence an approximation must be used. In the simplest case this can be made with a short sharp pulse sent to a digital to analogue converter and then on to a speaker, alternatively a starter's pistol is commonly used. The response of the system, measured by a microphone, is the IIR convolved with the input pulse shape, therefore the de-convolution of the system response with the input pulse shape can be used to obtain the IIR. Due to the short duration of a simple pulse little energy is used to probe the system. In addition, the shape of the signal means that there is a low immunity to background noise. As a result the IIR inevitably has a poor signal to noise ratio.

The limitations of a short pulse mean that other techniques have to be implemented to obtain an IIR with a higher signal to noise ratio. In these techniques the system is excited with a known signal and post processing applied to obtain the input impulse response. The post processing is always such that if applied to the input signal itself an impulse, or a close approximation, is obtained. In all cases the input signal itself bears no resemblance to an impulse. Commonly used signals include Maximum Length Sequence (MLS), Golay codes, Linear Sine Swept (LSS) and Exponential Swept Sine (ESS). The generalised behaviour of a system to an input is outlined in Figure 9. The linear impulse response of the system, $h(t)$, can be estimated by knowledge of the input signal, $x(t)$, and of the output signal, $y(t)$. Since it is the response of the linear system that is of interest it is necessary to minimise the influence of the not linear, time variant component (harmonic distortion) as well as noise [13].

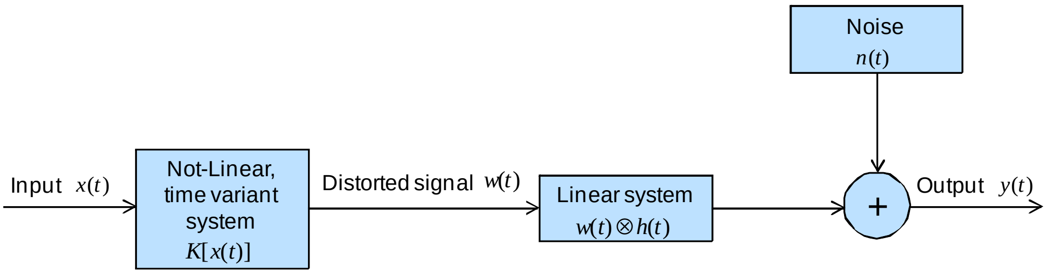

Figure 9: Generalised behaviour of a system to an input $x(t)$.

Of all the excitation signals, Maximum Length Sequence (MLS) is still the most widely used and so was chosen for this research.

4.1 Maximum Length Sequence

For MLS, $x(t)$ is a pseudo-random periodic binary signal. It is generated using linear feedback shift registers (a sequence of bits whose state changes with each time step - a bit is removed from the right and a new bit added to the left, the new bit's value is a linear function of the sequence's previous state). The length of a sequence n is defined in Equation (1), where m is the length of the register.

$$n=2m-1 \tag{1}$$

In appearance the signal is very similar to white noise but has the advantage over white noise that any sequence can be reproduced (the signal is deterministic), this is of particular importance for use in post-processing. The apparent random nature of the signal is the key to its high immunity to background noise. The system response is comprised of the superposition of a series of scaled input signals. This means that if the background noise contains the same shape as the input signal it will contribute a lot to the response. By contrasting the simple pulse discussed previously and the MLS signal it can be seen that such a simple pulse might be very common in background noise however the complex MLS signal is unlikely to be. As such, MLS has a much higher signal to noise ratio than a simple pulse.

The key to obtaining the impulse response from an excitation with an MLS signal lies in the auto-correlation properties of an MLS, defined in Equation(2) where ρ the auto-correlation, n is the MLS sequence length defined in Equation (1), and i is the offset between the two signals [14]:

$$\rho = \begin{cases} 1 & \text{for } i = 0 \\ -\dfrac{1}{n} & \text{for } 1 \le i \le n-1 \end{cases} \tag{2}$$

Equation (2) states the value of the auto-correlation of the MLS signal, which is a calculation in which the two signals are shifted relative to each other. The auto-correlation of a perfect impulse has a value of one when the two signals lie on top of each other (i=0) but zero for all other values of i. As can be seen, an MLS behaves like a near perfect impulse but for a non-zero value when $i \neq 0$. Since the magnitude of this non-zero value is dependent on the length of the MLS signal, an improved approximation is obtained as the length of the sequence is increased. It is this near perfect impulse that makes the MLS technique appropriate for APR. Since the auto-correlation gives a good approximation of an impulse, the cross-correlation of a systems response to an MLS signal with the MLS signal yields a good approximation of the input impulse response of the system.

When carrying out MLS there are constraints placed on the input signal. Since the MLS excitation signal is periodic, the convolution of this signal with the IIR is a periodic system response. As such to obtain an accurate IIR the periodic system response must be measured. To this aim the excitation signal must be sent at least twice, back to back. Since the excitation is now periodic, to avoid time-aliasing the excitation signal must be at least twice as long as the expected length of the system response. This can be determined by measuring the reverberation time of the system, which is defined as the time taken for the sound level to drop by 60dB after a sound source is stopped (note: a change in power ratio by a factor of two corresponds to a 3dB change). Another constraint of MLS is that the system under test should exhibit little harmonic distortion. If this is not the case then the harmonic distortion introduced appears in the resulting IIR as spurious peaks. These peaks are not removed by averaging with the same excitation signal, since though their locations appear random they are in fact well defined by the harmonic distortion of the system and the shape of the MLS sequence [15].

4.2 Extraction of the Input Impulse Response of the system

When the MLS technique is carried out on a system under test, the IIR obtained has contributions from both the system under test and the electro-mechanical equipment used to create/measure the acoustic signal. This is due to the inability of the electro-mechanical equipment to perfectly reproduce/measure an MLS sequence (and is thought to be associated to the inability of the speaker and microphone to reproduce and measure very low frequencies, respectively). Instead of obtaining a very sharp impulse (Dirac) in the signal calculated from the cross-correlation step detailed previously, the impulse is generally replaced by a wider pulse, with undulations on one or both sides, arising from the transient behaviour of the electro-mechanical equipment. This pulse shape has to be removed from the processed MLS response to get the IIR of the system under test.

For this purpose a further de-convolution must be carried out. First the pulse shape due to the electro-mechanical equipment has to be determined. The preferred method to achieve this in acoustic pulse reflectometry is by use of the previously mentioned source tube. The source tube is used to insert a gap between the microphone and the entrance to the system under test. This gap allows for the input signal to be measured in isolation without reflections from the object interfering. By measuring the input signal in isolation, the shape of the pulse actually produced can be determined. Once this pulse shape is known, it must be de-convolved with the cross-correlated MLS response to obtain the IIR of the system under test.

4.3 Interpretation of the Input Impulse Response

As discussed, the IIR obtained by carrying out APR on a pipe is related to cross-sectional area changes along the pipe. Although in practice more complicated than the theoretical approach, the basic method is the same. An impulse is used to excite a system, and at each of the cross-sectional area changes in the system reflection and transmission occur. The response of the system is the input impulse response. This IIR therefore consists of a series of spikes with both positive and negative amplitudes. The size and amplitude of the spikes is determined by the form and size of the cross sectional area changes (which are related to changes in acoustic impedance). Due to the nature of reflections of acoustic waves at increases/decreases in cross sectional area, an increase is distinguished by a negative spike while a decrease is distinguished by a positive spike. For a simple system it is possible to determine the location of increases and decreases in cross-sectional area simply by examining the IIR. However for more complicated system bore reconstruction can be carried out.

4.4 Bore reconstruction

A number of reconstruction algorithms exist including the direct solution developed by Ware and Aki [11]. However, the Ware-Aki algorithm does not take into account losses, and in many cases the losses cannot be assumed to be small enough to ignore if accurate bore reconstruction is to be obtained. Many attempts to compensate for losses have been made. One such algorithm, developed by Amir *et al*. [16] is the layer peeling algorithm.

For accurate bore reconstruction to be possible another constraint must be placed on the excitation signal used. The reconstruction algorithms assume that only plane waves can propagate in the pipe. For this condition to be true a cut-off frequency must be defined and the excitation signal must not contain frequencies above this. For an air filled tube the first non planar mode is determine by Equation (3) [17] where ω_c is the angular frequency [in Hz] of the first non planar mode of an air filled tube, c the speed of sound [in m.s^{-1}] and r the radius of the pipe [in m]. Below this frequency only plane waves propagate.

$$\omega_c = 1.84c/r \qquad (3)$$

5 Trials

A test rig was built to examine the use of Acoustic Pulse Reflectometry as a means of inspecting drains. This experimental drain was constructed from 300mm diameter pipe using materials identical to those found on the Highways Agency drainage network. The 300mm diameter pipeline was assembled from 6m long sections, connected together by push-fit joints and ring seals. The pipeline was situated above ground and indoors.

It was the aim of these trials to demonstrate that APR can provide information about the condition of a pipeline. In doing so it was also possible to demonstrate how an acoustic method would be preferable to both light and air packet based approaches.

A key issue with light and air packet based approaches was likely to be the complexity of the equipment required. This was not the case for an acoustic method. A standard bass speaker, microphone, amplifier and data acquisition device with digital to analogue and analogue to digital channels were purchased, as well as the necessary cabling. All the equipment was readily available off-the-shelf and software was developed to generate the excitation signal and perform the data processing/display.

5.1 The excitation signal length

The APR was to be implemented using the MLS technique. For the method to be valid, the length of the sequence was required to be at least twice as long as the expected length of the systems response, measured as the reverberation time of the system. This was determined with the exit of the test pipe sealed. To assess the reverberation, an acoustic signal was produced covering the same range of frequencies to be used in the trials (see below). The response of the system was then measured, Figure 10. From this it was possible to determine the time taken for the sound level in the pipe to drop by 60dB after the signal was stopped. It was found to take approximately 6s, as such in the main trials a 12.6s MLS signal was used for the excitation (this was the shortest possible MLS signal which was at least twice as long as the reverberation time).

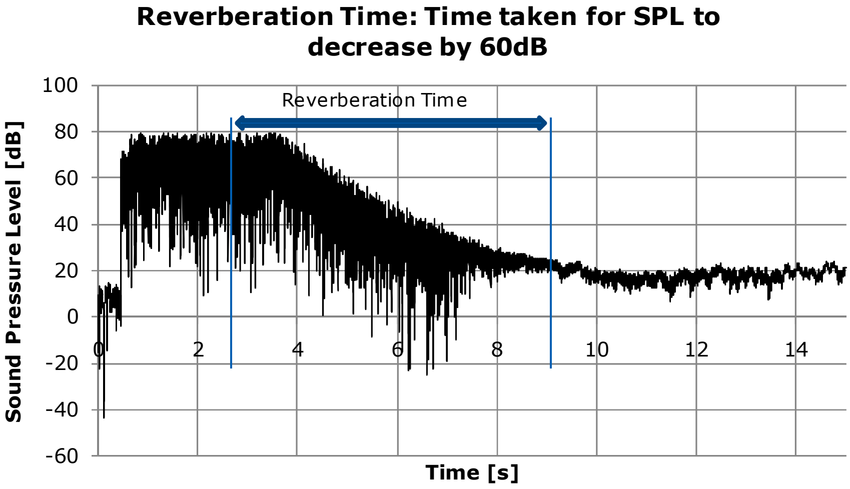

Figure 10: Reverberation of the MLS signal.

5.2 The cut-off frequency

It was also necessary to ensure that mainly plane waves were sent in the pipe by limiting the frequency of the excitation signal. As discussed in Section 4.4 this range is defined by Equation (3).

For the 300mm diameter pipe used, and taking c=346.3m.s^{-1}, the frequency limit was ω_c=676Hz. To impose this limit the MLS signal sent to the data acquisition device was clocked at 650Hz.

5.3 The main trials

One of the main issues with a light based approach was a requirement for a clear line-of-sight from entrance to exit of the section of pipeline under inspection. An experiment was set up as shown in Figure 11 to examine how an acoustic approach would cope with the lack of a line-of-sight, and as such demonstrate its advantage over a light based method.

Five sections of pipe where joined and a bend in the pipeline was produced. The speaker and microphone were placed at the entrance to the pipe, approximately 10cm apart. A source tube was not used in the trials, since it was impractical to have a perfectly uniform 30m tube in front of the pipe under test. The speaker did not completely fill the pipe, as such the system was not completely sealed at the entrance. The end of the pipe could be sealed using a stopper (also known as a "bung") screwed tight against the walls of the pipe.

Two sets of experiments were carried out, one in which the end of the pipe was open, and one in which the end of the pipe was sealed using the bung. A 12.6s long MLS signal was repeated twice and used to excite the system. While the excitation signal was being sent the response of the system was recorded and cross-correlated with the MLS excitation signal to obtain the IIR of the systems. The result of this post processing is shown on Figure 12.

The solid line corresponds to the result obtained when the end was open and the dotted when it was closed. Two pulses could clearly be seen separated by approximately 30m, the actual length of the pipe. In addition, features at a regular interval of approximately 6m could be distinguished. These features were related to the joints between the 6m long units of pipe. Up to approximately 32m the two IIR matched nearly perfectly, however after this point they become nearly mirror images. As was expected this deviation in the responses was due to the difference at the exit of the pipe. The closed pipe represented a decrease in the cross sectional area, and thereby a positive spike, while the open pipe represented an increase in cross sectional area, and so a negative spike was observed.

Figure 12 however does not represent the exact IIR of the pipe. As discussed previously, an input impulse response is the response of a system when excited by an impulse. In these trials the aim was to measure the IIR of the pipe, from this point referred to as the system. However, the IIR of the electro-mechanical equipment used to reproduce and measure the acoustic signal contributed to the results obtained. As such Figure 12 contains both the IIR of the system and the contribution (i.e. distortion) of the electro-mechanical equipment.

In an attempt to extract the system's IIR, the IIR of the electro-mechanical equipment was estimated. It was assumed that the pulse shape observed in the first 10m of Figure 12 was solely due the electro-mechanical equipment. This was known to be correct if the pipe contained no cross-sectional area changes in the first 10m that would cause a reflection in the signal. Though a fair approximation, from Figure 12 it could be seen that this was not entirely correct, with a joint feature clearly observed at approximately 8m. Since it was not possible to remove the effect of the joint, its contribution was assumed to be negligible. This estimation of the IIR of the electro-mechanical equipment was next de-convolved with Figure 12. The calculated system input impulse response can be seen in Figure 13. The features of Figure 13 were very similar to those of Figure 12, but with the pulse shape a better representation of an impulse. Though there was a high level of noise in the results, two impulses in each of the signals could clearly be observed. The first impulse, with the same polarity in both signals, is the excitation impulse emitted into the pipe. This excitation impulse travelled the length of the pipe without encountering any major cross sectional area change. On reaching the other end of the pipe the two signal exhibit very different responses. The closed pipe having a positive impulse, while the open pipe having a negative impulse. This difference was as expected, and clearly identified the differences in the open and closed pipes.

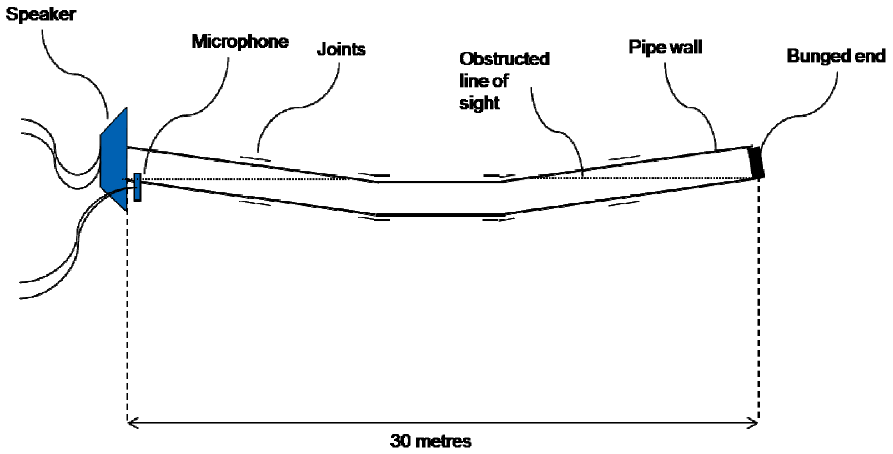

Figure 11: Experimental set-up with obstructed line-of-sight from entrance to exit.

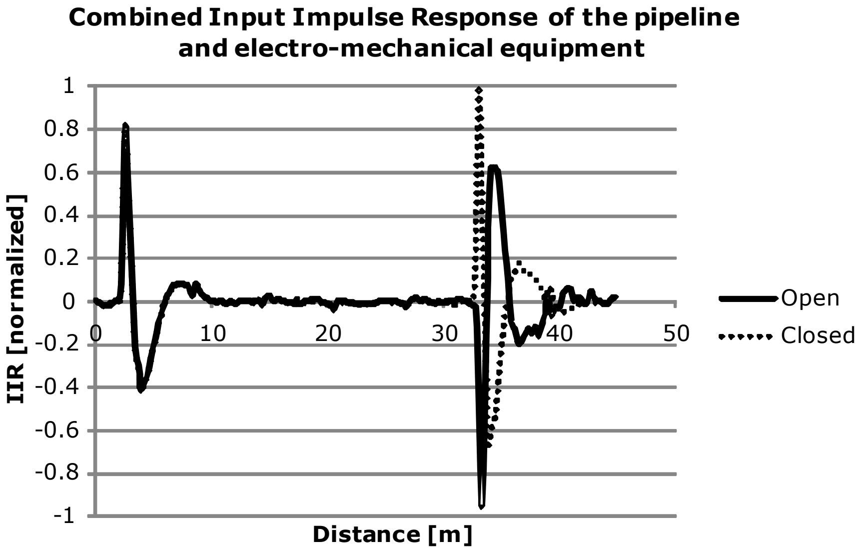

Figure 12: Cross-correlation of system response with MLS excitation signal.

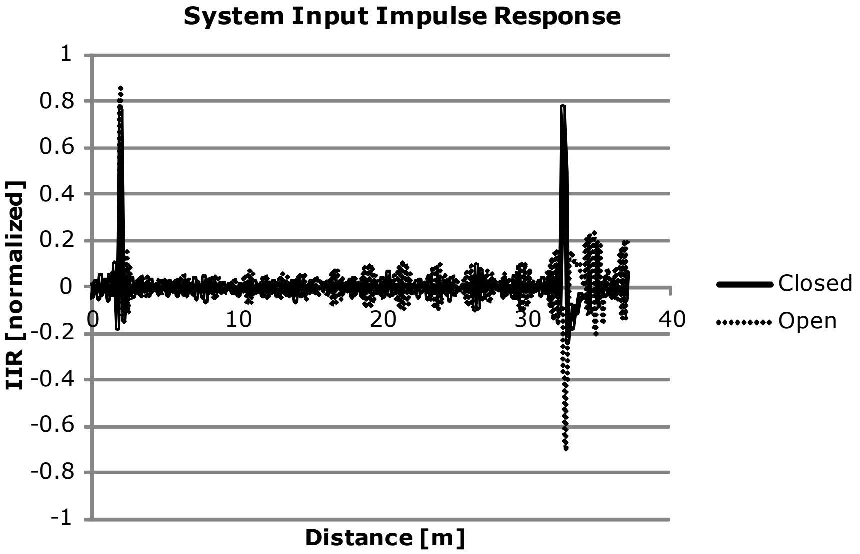

Figure 13: System IIR, obtained by de-convolution of the signal shown on Figure 12 with the electro-mechanical equipment's IIR.

5.4 Conclusion

The trials clearly demonstrate the ability of acoustic pulse reflectometry to gain details about the conditions of a pipe through a simple and quick measurement procedure, and without the need for a line-of-sight from one end to the other. Equipment placed at one end of a pipe could distinguish between pipes with a closed end or open end. In addition, this difference was correctly located within the pipe, with the length of the pipe accurately measured to 30m. In Figure 12 it was also possible to identify the presence and location of the joints between the 6m long units of pipe. However these features were not observable on Figure 13 due to the de-convolution with an imperfect IIR for the electro-mechanical equipment.

Although the trials have shown the significant potential of the technique to identify blocked pipes, it was not possible to successfully carry out bore reconstruction on the system's IIR to obtain the bore profile. Some notable issues were that it was difficult to isolate the shape of the pulse due to the electro-mechanical equipment, which is needed to extract the IIR of the system, and it was not impossible to separate the source reflections from those of the system under test.

6 Summary

Currently assessment of the Highways Agency owned drainage network is undertaken on a 10 year rolling inspection process using CCTV equipment. Such an assessment regime is unsuitable to practically identify problems requiring immediate treatment such as blockages or the build-up of debris. For this reason, this research set out to investigate methods for carrying out the inspection of drainage pipes that would show speed improvements over CCTV. As such, the method was required to be non-invasive, and viable with access to only the manholes. The method had to be capable of operating in pipelines constructed from preformed plastic units joined *in-situ,* with a diameter of 300mm. Approaches based on light, air packets and acoustic techniques were considered and an acoustic technique called the Acoustic Pulse Reflectometry was found to be the most appropriate. Table 1 presents the advantages and disadvantages of each approach.

Method	Advantages	Disadvantages
Use of light	• Lasers are available with high intensity beams, and as such long ranges • In theory, laser profiling is very accurate with a high resolution possible	• Requires a clear line-of-sight from one end of the pipe to the other • Effected by refraction and diffraction effects
Use of air packets	• Relies on physically introducing a "volume" of air which is going to travel at a speed substantially slower than the speed of light or sound and interact with features in the pipe: assuming that a "volume" of water would behave similarly, this is closer to the normal operation of the drain	• Difficulties in creating a stable air packet that would fill a pipe's diameter • Difficulties in reproducing air packets with the same shape consistently • High attenuation limits the travel of the air packet • Difficulties in sensing the shape of an air packet and determining its characteristics
Acoustic Pulse Reflectometry	• "Off-the-shelf" equipment required • No need for line-of-sight • High sensitivity to blockages and leaks	• Complex signal processing • Imperfections in the generation and acquisition chains affect accuracy and sensitivity

Table 1: Advantages and disadvantages of the various methods considered.

Experiments were carried out on a test rig built using materials comparable to those found on the Highways Agency drainage network. The 300mm diameter pipes were assembled from 6m long units, connected together by push-fit joints and ring seals. The drain was situated above ground and indoors.

To examine the ability of APR to inspect a pipe a set of trials were undertaken. The drain in question was bent so that no clear line-of-sight was possible from the entrance to the exit. Two conditions were investigated, one in which the exit of the pipe was left open, and one in which the exit was sealed using a bung. A 12.6s MLS signal was used to excite the system. Further processing of this response had to be carried out since it contained contributions from both the IIR of the pipe and the electro-mechanical system used to produce/measure the MLS signal. The resultant IIR of the pipe was determined and clearly showed difference between the sealed and unsealed pipe, and the location of the seal.

7 Way forward

The results of the experiments demonstrated that though no line-of-sight was available from exit to entrance of the pipe, the acoustic method identified was able to gain information, in less than 30s, about the condition at the far end of the pipe.

The implemented method used of off-the-shelf components, was repeatable, exhibited a high signal-to-noise ratio and seemed particularly sensitive to a number of features of interest for drain inspection. One of the main benefits of this approach compared to traditional techniques is that measurements would be extremely quick, which should make traffic management considerably easier, thereby decreasing the associated traffic disruption, potential danger exposure for inspectors and the overall burden/cost of the drain assessment.

The fact that the presence of the sealed joints were visible in the Input Impulse Response means there is potential to apply this method to test for leaks, either when a drain is in service or possibly at the construction stage (for instance to facilitate the rectification work by showing the location of the faulty joints).

However, these experiments were conducted on a single type of new pipe with perfectly clean walls laid off the ground in a laboratory. We do not yet fully understand:

- what the performance of the method would be in presence of organic or mineral contamination;
- how the results obtained off the ground will be transposable to buried pipes;
- what the effect of ambient and traffic noise and vibrations will be;
- how the system is going to change as the characteristics of individual components are gradually altered (with wear and tear, because of interferences, due to the use of the sound source/detectors in a wet environment, etc.);
- the resemblance of the response related to blockages of similar size but formed from tightly or loosely packed material, with a rough (more absorbent) or smooth (more reflective) surface, etc.
- which technique can be implemented to minimize the influence of, or compensate for, the transient electro-mechanical equipment characteristics;
- what type of excitation signal provides the most reliable results;
- how to cope with the absence or impossibility of using a source tube;
- whether acoustic waves of different frequencies interact differently with features of different size and what is the optimal set of parameters to use;
- how a fully contained portable device can be built to perform the measurement and processing in real time;
- if the method is significantly affected by small differences in, for instance, the positioning of the equipment inside the drain (making it impossible to compare different measurements);
- what the effect of junctions and inlets/outlets will be on the measured signal;
- if the method will be equally successful in pipes made with different materials, diameters, section length, cross-section (including egg-shaped), etc.

Therefore, although the acoustic technique identified was the most promising of those investigated, more work is needed to get a robust and reliable system useable for routine drain inspection. This research and development will need to tackle the questions listed above and extensively validate the approach by comparison of its actual performance against traditional inspection and test techniques.

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