LEA NG
INSTANTANEOUS FREQUENCY
ANALYSIS

by

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Summary

Leaking pipes are a primary concern for water utilities around the globe as they compose a major portion of losses. Contemporary interest surrounding leaks is well documented and there is a proliferation of leak detection techniques. Although the reasons for these leaks are well known, some of the current methods for leak detection and location are either complicated, inaccurate and most of them are time consuming.

Transient analyses offer a plausible route towards leak detection due to their robustness and simplicity. These approaches use the change of pressure response of the fluid in a pipeline to identify features. The method used in the current study employ a single pressure transducer to obtain the time domain signal of the pressure transient response caused by a sudden opening and closing of a solenoid valve. The device used is fitted onto a standard UK hydrant and both cause a pressure wave and acquire the pressure history.

The work described here shows that the analysis using Hilbert transform (HT), Hilbert Huang transform (HHT) and EMD based method is a promising tool for leak detection and location in the pipeline network.

In the first part of the work, the analysis of instantaneous characteristics of transient pressure signal has been calculated using HT and HHT for both simulated and experimental data. These instantaneous properties of the signals are shown to be capable of detecting the reflection from the features of the pipe such as leakages and outlet. When tested with leak different locations, the processed results still show the existing of the features in the system.

In the second part of the work, the study is based on newly method of analysing non-stationary data called empirical mode decomposition (EMD) for instantaneous frequency calculation for leak detection. First, the pressure signals were filtered in order to remove the noise using EMD. Then the instantaneous frequency was calculated and compared using different methods. With this method, it is possible to identify the leaks and also the features in the pipeline network. These were tested at different locations of a real water distribution system in the Yorkshire Water region.

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Abbreviations

DMA	District meter area
MSCL	Mild steel cement lined
PCCP's	Prestressed concrete cylinder pipes
PVC	Polynivyl chloride
EPA	Environmental protection agency
IWA	International water association
SIV	System input volume
NRW	Non revenue water
UFW	Uncounted for water
IWSA	International water supplying association
AWWA	American water works association
CIWEM	Chartered institution of water and environmental management
EGL	Energy grade line
ALC	Active leakage control
PLC	Passive leakage control
CARL	Current annual real losses
UARL	Unavoidable annual real losses
FT	Fourier transform
AM	Amplitude modulation
FM	Frequency modulation
STFT	Short time Fourier transform
HT	Hilbert transform
HHT	Hilbert Huang transform
TLM	Transmission line modeling

IF	Instantaneous frequency
GPR	Ground penetrating radar
PPA	Pressure point analysis
MOC	Method of characteristics
GA	Generic algorithm
ITA	Inverse transient analysis
SWDM	Standing wave difference method
PPWM	Portable pressure wave method
EMD	Empirical mode decomposition
IMF	Intrinsic mode function
NHT	Normalize Hilbert transform
DQ	Direct quadrature
TEO	Teager energy operator
DWT	Discrete wavelet transform
CWT	Continuous wavelet transform
STP	Standard temperature pressure
EEMD	Ensemble empirical mode decomposition
HS	Hilbert spectrum
SUNAS	Sheffield university network analysis software
LEL	Leakage economic level
MDPE	Medium density polyethylene
LRM	Leak reflection method

Nomenclatures

a	Wave speed of fluid (m/s)
a_i	Wave speed of i-th pipe (m/s)
a_0	Incoming wave speed (m/s)
A_i	Area of i th pipe (m 2)
A_0	Incoming pipe area (m 2)
b	Time translation parameter
$C(k)$	Wavelet coefficient
C_d	Discharge coefficient
c_1	The first IMF
c_i	IMFs
c_n	nth IMF derive from sifting process
D	Pipe diameter (m)
$d(j,k)$	Detail coefficients at level j and location k
d	Distance between access points (m)
f	Frequency
$F(w)$	Fourier transform of f(t)
g	Gravity vector (m / s^2)
j	$\sqrt{-1}$
J	Number of levels of DWT decomposition
k	Elastic property (n/m^2)
M	Number of data point
P	Pressure (Pa)
Re	Reynolds number of the flow (related to the pipe diameter)
r	Reflection factor

s	Transmission factor
t	Time (s)
t_{peak}	Time delay (s)
t_a	Time instance (s)
u	Velocity (m/s)
V	Velocity vector (m/s)
w	Angular frequency
$w(t)$	Window function
$x(t)$	Time domain factor
X_{leak}	Position of leak
ΔH	Change in head (m)
ΔH_0	Head of pressure wave (m)
ΔH_R	Head of reflected wave (m)
ΔH_s	Head of transmitted wave (m)
ΔP	Change of pressure (Pa)
ΔV	Change in fluid velocity (m/s)
Δf	Frequency resolution
Δt	Time resolution
ε	Turbulent rate of diffusion (m^2 / S^3)
k	Turbulence intensity (KW / m^2)
μ	Dynamic viscosity (Pa.s)
ν	Kinematics viscosity ($Kg.m.s^{-1}$)
ρ	Fluid density ($Kg.m^{-3}$)
τ	Position in time of Gaussian window
$S(\tau, f)$	Short time Fourier transform of x(t)

$\psi_{a,b}(t)$	Scale version of base wavelet CWT
$\psi_{j,k}$	Scale version of base wavelet for DWT
$A_j(t)$	Wavelet approximation
$D_i(t)$	Detail coefficient of DWT
$\psi(t)$	Wavelet function
$\phi(x)$	Scaling function
C_ψ	Admissibility wavelet condition
x, y, z	Cartesian coordinates

Chapter 1

Introduction

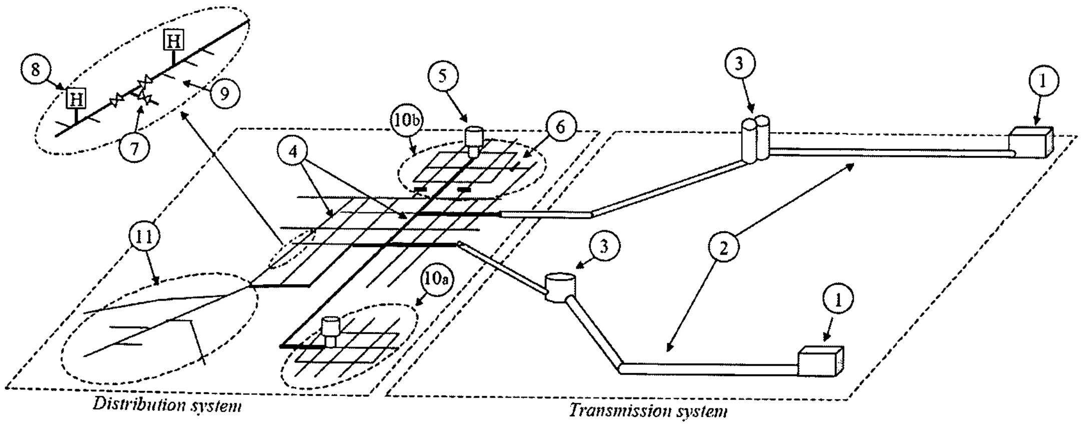
Water is an essential element for life which is necessary for the survival of human beings and is scarce supply in most parts of the world. According to the Global water Supply & Sanitation assessment report [1], at the beginning of 2000, one sixth (1.1 billion people) of the world's population was without access to a potable water supply. As a result, there is an increasing awareness around the world of the need to prevent the loss of this natural resource. In the last decade, with changing climatic conditions, population growth and the increasing cost of access to water resources, many countries must cope with limited resources. In many countries water companies have identified the problem and measures are already being undertaken to foster an approach of better management of the water distribution systems [2]. These efforts come from effective water utilisation, reduction of wastage and control policies to demand management strategies. Water loss from the water distribution systems remains one of the main problem issues facing not only developing, but also developed countries throughout the world. Aging pipes is one of the predominant factors to the water loss as water transmission and distribution networks continue to deteriorate with time [3].

It is not practical to prevent many pipes from failure since a significant proportion of pipelines was installed in the first part of 20th century and are now in poor condition. Additionally, although, pipeline systems are currently designed and constructed in accordance with relevant quality standards set by authority to maintain their integrity, leaks are an inevitable problem even in new pipeline networks. In general, pipeline systems can be considered to be in an acceptable state if they have an average annual pipe break ratio below 40 per 100 km [4].

A key to developing a leak detection strategy is to monitor the system from an early stage. Leakage occurring from transmission and distribution mains normally cause large pressure surge events, sometimes catastrophic, which can cause damage to road infrastructure and vehicles. Furthermore, due to different topology and hydraulic characteristic's component of the water distribution system, separate leak detection and location methods have been proposed in the past. As it will be presented in the review of the literature in the next chapter, great efforts have been made in order to develop methodologies or devices for determination of leaks, with some limited success.

1.1 Structure of a water supply system

Water systems are lifelines of communities. Generally, the design and complexity of drinking water supply systems may be different significantly, but all of them have the same basic principle; to convey the water from the source such as treatment facility to their customers. They are made of such items as valves, fittings, thrust restraints, pumps, reservoirs, and, of course, associated pipe features. Source for municipal water supplies consists of wells, rivers, lakes, aquifers and reservoirs. It is estimated that about two thirds of the water available for public supplies around the world comes from surface water sources. An example of the structure for water supply system from water treatment plant to a distribution system is shown as Figure 1-1.



1. Water treatment plant; 2. Transmission pipeline; 3. Reservoir; 4. Distribution mains; 5. Tower; 6. Permanently closed valve; 7. Isolation valve; 8. Fire hydrant; 9. Service connection; 10. District metering area (DMA), a) as constructed, b) artificially created using permanently closed valves; 11. Branched section of the network.

Figure 1-1: Example of the structure for water supply system [3].

The whole water system can sometimes be divided into two parts [3]: the transmission lines and the distribution system. The transmission system is that part of the system which conveys a large amount of water over great distance typically from the source to the distribution system. It may consist of treatment facility and storage reservoir. On the other hand, transmission lines have few, if any, interconnections. Such lines can be built underground as well as aboveground with various lengths. In some areas, the water has to be distributed over distance of hundreds of kilometres. The main design consideration for a transmission line is that of internal pressure. Normally, individual customers are not served directly from these transmission pipelines.

The distribution piping system transport water to the residential area. In general, a distribution system has a complex topology and contains a large number of elements. It consists of a distribution main and a service connection. Distribution mains can be considered as an intermediate step towards delivering water to the end customers. It includes many connections, loops, and so forth. As shown in Figure 1-1 an urban distribution system is a combination of looped and branched topologies. The size of service pipes is smaller than distribution mains and connected from street to property.

Looped systems are preferable compared to branch system because, combination with sufficient valving, they can offer an extra level of reliability [5]. However, the installation cost for a looped system is more expensive than for a branched system. Figure 1-1 also displays closer view of the parts of the water distribution system at the street level. District meter areas (DMAs) have been installed to monitor the flow into supply zones. As we can see, a fire hydrant connector point is another common element in both transmission and distribution systems. Meanwhile, various types of valve have been installed for the purpose of isolation in case of failure remediation or maintenance work by the water companies. Distribution systems are made up of an interconnected pipe network. Tees, elbows, crosses and numerous other fittings are utilized to join and redirect section of pipes. The installation of these fittings and connections need great care to prevent longitudinal bending and differential settlement.

1.2 Pipe assets

A variety of materials and technologies have been utilized in the manufacture of water pipe supply for transmission, distribution and service lines. The material used depends on the year of installation and the diameter of the pipe. The most common materials of service connection pipes are steel, plastic and lead [6]. For larger diameters such as transmission pipelines (diameter over 300mm), steel, mild steel cement lined (MSCL) or prestressed concrete cylinder pipes (PCCPs) are usually used. Cast iron or asbestos cement is found in older distribution systems. This distribution of pipe materials in water pipeline systems is changing as a result of the current extensive use of plastic pipes[3].

The most extensive water distribution system in ancient times was built by Romans. The first aqueduct that built by Romans was in 312 B.C., which conveyed the water for long distance by means of gravity through a collection of open and closed conduits. The Romans also introduced lead pressure pipes. In the 13th century, a water supply system in Europe was built in London when a 5.5 km lead pipeline was installed to convey water from Tybourne Brook to London. Sanks [7] reported that in the mid 1700s water mains were constructed by the mixture of wood, cast iron and lead pipe. Some wooden pipes are still in service today. During the 1800s, cast iron pipe gradually replaced wooden pipes. For a long time, cast iron was used and had an excellent record of service but since the 1920s, due to introduction of better materials and pipe making technology many new pipes have been laid. For example, steel, ductile iron, asbestos cement and concrete pipes have been introduced in the water supply system around 50 years ago. Meanwhile, plastic materials have been popular and contribute a large proportion of current installations since its introduction in 1970. Overall, considering the contribution of pipe materials used in the water supply system, it is estimated that the average age of pipes in developed countries is about 50 years. Many cities experienced periods of urban expansion during late 1800s, around World War I, during the 1920s and post World War II brining them an enlargement of the water distribution systems. As a result, the use of old pipe networks for long periods of time has been affected by deterioration processes ever since the initial installation. As point out by Misuinas [3] pipe failure can be described as multistep process as shown in Figure 1-2.

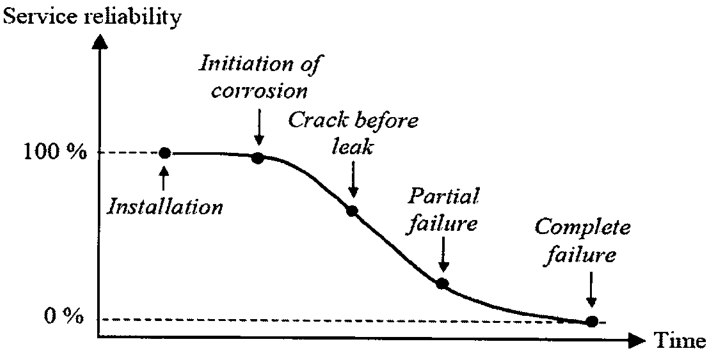


Figure 1-2: Pipe failure development [3].

The process consists of installation, initiation of corrosion, crack before leak, partial failure and complete failure. The corrosion develops internally and externally after the pipe has been operated for some time. These processes can cause anomalies such as cracks, corrosion pits and graphitisation. In some cases, cracks can be initiated by mechanical stress. None of them are severe enough to induce leaks, but the residual strength of the pipe is reduced below the internal or external stresses and the pipe wall breaks. Therefore, depending on the size of the break the leak or burst will be initiated. Finally, the complete failure of the pipeline can be caused by a crack, corrosion pit, pre-existing leak burst or interference by third party. As a result, the water can appear on the ground surface.

A failure sequence as shown in Figure 1-2 is not necessarily applicable to all pipes. As reported by Wang and Aatrens [8] the stress corrosion cracks are likely developed with time, that is, active cracks. The materials of the pipe also influence the temporal development of the pipe failure [9]. For steel and ductile iron pipes leak normally occur before they break. It's different with the cast iron and larger diameter prestressed concrete pipes where break come first before the leak. Meanwhile, PVC and plastic pipes can do either depending on the installation and operational conditions. Obviously, the failure development is more likely to be specific for a particular pipe and very difficult to predict. Involvement of third parties and other external forces make the situation become more complex and challenging. Failure of early leak detection of the water pipe supply can cause big disasters such as flooding, water pressure drop and costly waste from the water distribution system.