Non-invasive Acceleration-based Methodology for Damage Detection and Assessment of Water Distribution System

Masanobu Shinozuka* and Debasis Karmakar

Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697, USA.

Pai H. Chou and Sehwan Kim

Department of Electrical Engineering & Computer Science, Univ. of California, Irvine, 92697, USA.

Hong Rok Kim

Center of Embedded Software Technology, Korea

Lu Fei

College of Civil Engineering, Southeast University, China

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Abstract. This paper presents the results of a pilot study and verification of concept of a novel methodology for damage detection and assessment of water distribution system. The unique feature of the proposed noninvasive methodology is the use of accelerometers installed on the pipe surface, instead of pressure sensors that are traditionally installed invasively. Experimental observations show that a sharp change in pressure is always accompanied by a sharp change of pipe surface acceleration at the corresponding locations along the pipe length. Therefore, water pressure-monitoring can be transformed into acceleration-monitoring of the pipe surface. The latter is a significantly more economical alternative due to the use of less expensive sensors such as MEMS (Micro-Electro-Mechanical Systems) or other acceleration sensors. In this scenario, monitoring is made for Maximum Pipe Acceleration Gradient (MPAG) rather than Maximum Water Head Gradient (MWHG). This paper presents the results of a small-scale laboratory experiment that serves as the proof of concept of the proposed technology. The ultimate goal of this study is to improve upon the existing SCADA (Supervisory Control And Data Acquisition) by integrating the proposed non-invasive monitoring technique to ultimately develop the next generation SCADA system for water distribution systems.

Keywords: Water pipe monitoring, MEMS sensors, ruptures, wireless sensor network

1. INTRODUCTION

Urban water distribution systems, particularly underground pipeline networks, can be damaged due to earthquake, pipe corrosion, severely cold weather, heavy traffic load on the ground surface, and many

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* Corresponding Author, E-mail: shino@uci.edu, Telephone: +1 949 824 9379

other man-made or natural hazards. In all these situations, the damage can be disastrous: interruption of potable water supply will create major human health problems, let alone all kind of inconveniences; pipe damage may result in reduction in the water head diminishing post-earthquake firefighting capability; water leakage at high pressure may threaten the safety of nearby buildings due to scouring of their foundations; flooding could create major traffic congestion if a pipe ruptures under a busy street. Yet, the current technology is not capable of accurately identifying the location and extent of the damage easily and quickly, even after a major rupture (including severe damage) event. This paper demonstrates the use of a sensor network for identification of location and extent of pipe rupture in real-time so that emergency response measures can be rapidly implemented to minimize disaster consequences.

This paper focuses on the identification of pipe rupture arising from several sources other than earthquake ground motion. These sources include corrosion and aging, excessive surface traffic loading, soil failure, etc. For identifying earthquake induced pipe ruptures, sophisticated analytical models considering the interaction between soil and pipe networks are needed, and they are currently being developed on the basis of more elaborate laboratory and field tests. However, the information obtained from the present pilot study is providing valuable knowledge-base for the future study. For this reason, the present paper develops and demonstrates an advanced sensor network for real-time monitoring and condition assessment of utility water distribution systems such as the Los Angeles water network, which recently suffered from a large number of non-seismic episodes of pipe ruptures.

The sensor network developed in this paper consists of a platform of multiple real-time wireless and energy-efficient sensors and sensor nodes. Each node transmits wirelessly the data sampled by Micro-Electro-Mechanical Systems (MEMS) and other emerging sensors. Collectively, these sensors have been assembled into two different sized packages: the full-sized version called PipeTECT (Shinozuka et al. 2010), and the miniature version called Eco (Park and Chou 2006). Both have been designed, assembled, and tested in the laboratory as well as in the field at UC Irvine and are particularly being tailored for civil engineering applications. The current-generation PipeTECT and Eco are equipped with triaxial MEMS accelerometers. The accuracy of these devices has been verified against traditional high-precision piezoelectric accelerometers in the field and by shake-table tests. Indeed, these tests have validated the ability of the sensor to make the low-frequency observations necessary for monitoring and remotely visualizing (by wireless communications) large-size civil engineering structures in real-time. The substantial cost-effectiveness, robustness, durability, small size and light weight of PipeTECT and Eco sensors make it possible to densely configure observational networks for many types of civil infrastructure systems such as bridges, buildings, and pipeline networks.

This study concentrates on the application of sensing technology to pressurized water distribution systems, and we develop methods for rapidly detecting and locating the source of anomalies in the water system. Such anomalies can be caused by one of many events such as pipe rupture and pump failure. To develop a novel means of identifying the location and extent of pipe rupture, we take advantage of two major hydraulic behaviors. First, the temporal pressure change is larger at a location closer to the source of transient and decays with distance in both pipe directions, as the numerical simulation using transient hydrodynamic analysis software shows. Therefore, if we install populated pressure sensors throughout the water network, say at each network joint, and continuously monitor the pressure there, the rupture location(s) can be identified in the pipe segment between the two adjacent joints where the local maximum water head gradient (MWHG) are observed simultaneously. However, additional study is needed to confirm a reliable correlation between the extent of the rupture and maximum MWHG values. Second, experimental results show that a sharp change in the water pressure is always accompanied by a sharp change in the acceleration on the pipe surface at the corresponding location along the pipe. This makes it possible to replace the entire process of water pressure monitoring with acceleration monitoring on pipe surface. The latter is significantly less costly compared with the former, because MEMS acceleration sensors for noninvasive sensing are generally much less expensive than pressure gauges for pressure monitoring in an invasive mode.

Thus, monitoring is made not for MWHG but for MPAG (maximum pipe acceleration gradient). As a first step, using a small-scale pipe network, this paper shows the result of a laboratory experiment that serves as the proof of concept of this new technology, which represents a prototype of the next generation of SCADA (Supervisory Control And Data Acquisition) for water distribution systems.

2. INVASIVE DAMAGE DETECTION USING HYDRAULIC TRANSIENT

2.1 Related Studies

Representative previous studies performed for detection of physical damage in water pipes are reviewed. None of them uses pipe acceleration for identification of location and/or extent of pipe rupture.

Liou and Tian (1995) detects pipeline ruptures based on the acquisition and transient analysis of real-time data.

Gao et al. (2005) uses correlation techniques for leak detection and location identification by analyzing the acoustic wave associated with leakage. These techniques are satisfactory for metal pipes, but they are unreliable for nonmetallic pipes in which the acoustic signals attenuates very rapidly.

Ferrante and Brunone (2003) applies several signal processing techniques to the pressure signal in the frequency domain, such as harmonic and wavelet analysis. Such techniques are used to enhance the disparity of the defective signal compared to the benchmark or non-defective signal. Also, wavelet techniques are efficient in detecting any singularity associated with the noise from the discharge.

Wang et al. (2002) detects damage in the pipelines by measuring damping of the transient events based on the fact that the different frequency components are damped differently in the presence of a rupture.

Liggett and Chen (1994) calibrates and determines rupture or unauthorized use in the pipeline systems based on inverse transient analysis in the pipe networks. These techniques solve the inverse problem from the measured pressure head data to detect the extent of rupture but involve extensive computational effort after the relevant data are collected. However, no single method can always meet operational needs from an accuracy and cost point of view (Furness and Reet 1998).

Hunaidi and Chu (1999) characterizes the frequency content of sound/vibration signals from leakage in plastic pipes as a function of leak type, flow rate, and pipe pressure. In this study, acceleration of the top surface of the fire hydrant instead of the pipe surface acceleration is used to identify leak characteristic.

2.2 Hydraulic Transients

A hydraulic transient represents a temporary, often violent, change in flow pressure, and other hydraulic conditions in a water distribution system from an original (first) steady state to a final (second) steady state the system achieves after the effect of the disturbance that caused such a transient is absorbed into the second state. The disturbance includes such events as a valve closure or opening, a pump stopping or restarting, and pipe damage or rupture leading to substantial water leakage. The transient can produce a significant change in the water head and pipe pressure. It is envisioned that the sudden change of such pressure will generate a measurable pressure wave and can be used for detection and localization of pipe damage. If the magnitude of this transient pressure is beyond the resistant capacity of system components, then it can induce a significant damage on the pipes, possi-

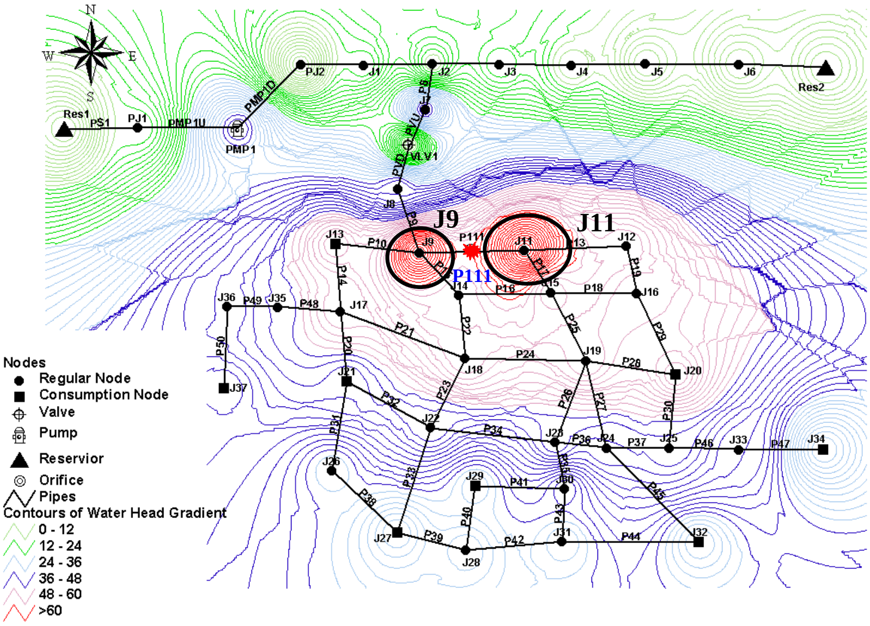
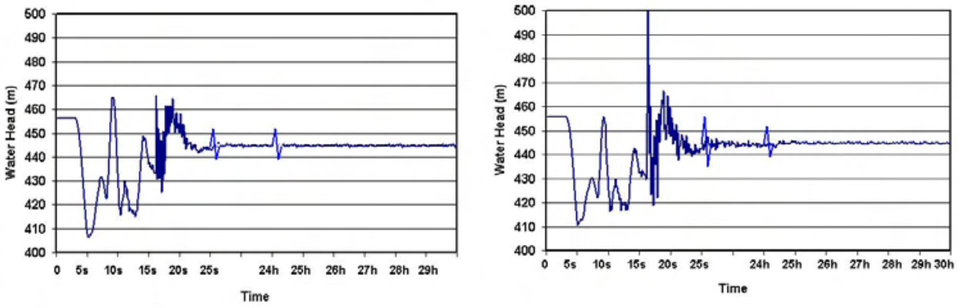
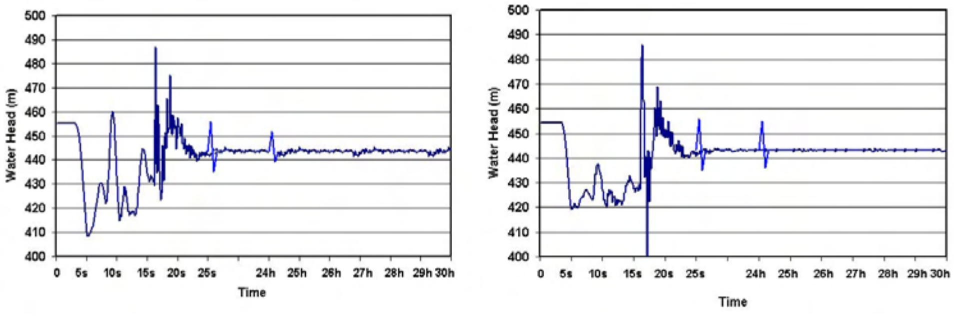


Figure 1. Distribution of water head gradient due to pipe P111 break.



(a) transient water head at Joint 9 due to a rupture in pipe 111

(b) transient water head at Joint 11 due to a rupture in pipe 111



(c) transient water head at J13 due to pump stop

(d) transient water head at J20 due to pump stop

Figure 2. Nodal water head time histories under damage events

bly resulting in equally significant system failures. Therefore, it is important to simulate the transient behavior of the water system under various adverse scenarios in order to understand the magnitude of these effects.

In this study, the industry-grade computer code HAMMER (HAESTAD Press 2003) is employed to generate time histories of key hydraulic parameters (primarily water head and flow rate). Fig. 1 shows an example hydraulic system for which analysis is carried as in *HAMMER User's Guide*. This water system consists of two reservoirs, one pump, one valve, 38 nodes and 54 pipe links. In the following, we first consider a case in which a pipe rupture occurs at the midpoint of link 111. In this case, a new node is created at the rupture location in this link (double circle in Fig. 1), and the numerical analysis continues. The time history of the computed water head at Joints 9 and 11 are plotted respectively in Figs. 2(a) and (b). Secondly, we consider a sudden stop of the pump station (node PMP1) due, for example, to seismically induced power blackout. The corresponding water head transient behavior is quite dramatically time variant, as shown in Figs. 2 (c) and (d), computed respectively at Joints 13 and 20. The water head transient behaviors under other pipe-damage scenarios with appropriate physical parameters of nodes and pipes are shown in Shinozuka and Dong (2005).

3. PROPOSED METHOD OF RUPTURE DETECTION

3.1 Noninvasive Method Using Acceleration Gradient

A method of rupture detection and localization, including the identification of malfunctioning equipment (typically pumps) is described here based on the comparison of the hydraulic parameters (water head in this case) before and after each damage event. For the primary purpose of a rapid detection and localization, it is most effective to catch the sign of abrupt change at the outset of the event. Fortunately, for a sudden change such as a pipe rupture and pump stoppage, the response of the network is rapid particularly in the neighborhood of the source. This suggests that some measurable signature that indicates the rapidity of this change can be used for the purpose of such an identification. One convenient quantity that serves this purpose is the water head gradient as defined below.

$$D = \left| \frac{H_2 - H_1}{t_2 - t_1} \right| \tag{1}$$

Here, H_1 and H_2 are the water head at a joint of interest at time t_1 and t_2, respectively. In this study, $t_2 - t_1 = 0.2$ (seconds) is used for computation.

During the normal steady state operation, D is usually negligibly small. In this paper, the water head gradient measured at the joints are integrated into a GIS platform for real-time visualization and for other advantages. Fig. 1 shows the distribution of water head gradient D in a contour plot in the extended network space for the convenience of visualization. The contour plot indicates that the damage location can be identified to be in Pipe 111 between nodes J9 and J11 where the water head gradients are locally at their maxima.

3.2 The Novelty of the Method

In this section, we introduce a novel rupture detection method based on a wireless MEMS-sensor network that monitors the pipe surface acceleration typically at each network joint in a non-invasive fashion and computes in real-time a measure of acceleration-change. To be more specific, MEMS sensors are installed at all the joints in the pipe network so that at least two end joints of every link of the network are monitored. When a rupture occurs in the network, the sudden disturbance in the water flow and pressure induces corresponding sudden change in the acceleration of pipe vibration. This change in the pipe acceleration is measured, and on the basis of these acceleration data, the location of

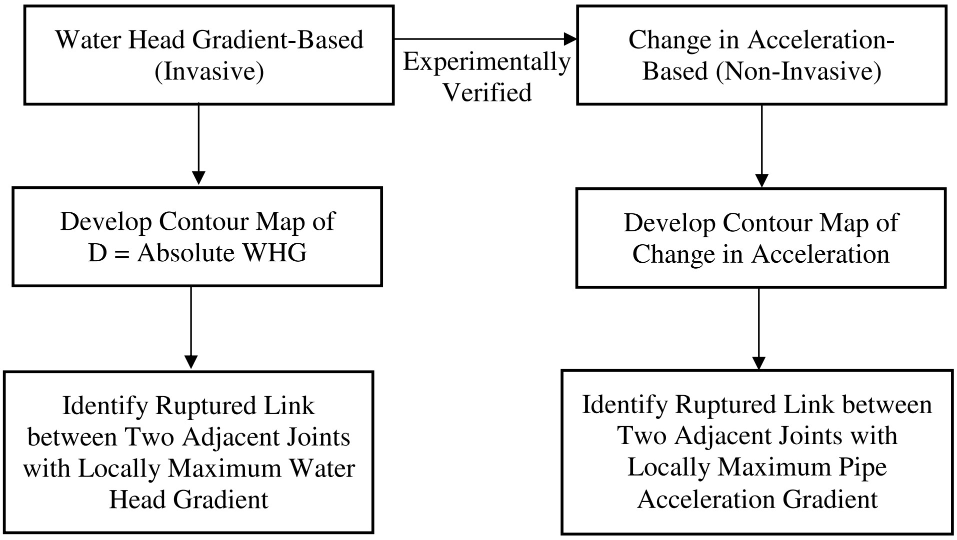


Figure 3. Damage Identification Methodology

the pipe rupture can be found in the pipe segment between the two end joints where the acceleration gradient values form local maxima. This is consistent with the result of an analytical simulation as shown in Fig. 1 demonstrating that the rupture is found between two end joints where the water head gradient form local maxima. This procedure, utilizing the non-invasive pipe surface acceleration measurement, facilitates a simple and cost-effective identification of ruptured pipe segment. Fig. 3 shows a comparison between the proposed non-invasive local maximum pipe acceleration gradient (MPAG) method (right column) and the invasive local maximum water head gradient (MWHG) method (left column). We note that the development of the exact correlation between the water pressure and the corresponding acceleration on the pipe surface needs further analytical study assisted by calibration on the basis of small scale model tests, and the field tests using actual water systems. For the field test, we plan to take advantage of scheduled events by the system owner/operator including valve opening and closing, switching on and off the pumps, and water discharge. We intend to make best out of these field experiments to calibrate in developing analytical models for the water pressure-pipe acceleration correlation.

3.3 The Correlation between Water Pressure and Acceleration

Pressure variations and flow-induced pipe vibrations are two strongly correlated quantities. The internal pressure p of a pipe can be expressed as $p = p_o + dp$, where p_o is the nominal pressure and dp is the pressure variations. Since the nominal pressure p_o does not contribute to the flow-induced pipe vibrations, only the pressure fluctuations dp will be considered. The pressure dp is balanced by the elastic stresses, p_{el}, and the inertia stresses, p_{in}, in the pipe wall, i.e., $dp = p_{el} + p_{in}$. Assuming F_{el} is the unidirectional force developed against the pipe wall, then:

$$\frac{F_{el}}{A} = \frac{p_{el} D l}{2tl} = \frac{p_{el} D}{2t} \tag{2}$$

where A is the cross sectional area, D is the pipe diameter, l is arbitrary length of the pipe, and t is the pipe wall thickness. Hook's law declares:

$$\frac{F_{el}}{A} = E\varepsilon = E\frac{\pi\delta_D}{\pi D} = E\frac{\delta_D}{D} \tag{3}$$

where, E pipe's elastic modulus, ε strain, δ_D pipe's diameter deformation. From Eqs. 2 and 3:

$$p_{el} = \frac{2tE\delta_D}{D^2} = \frac{4tE\delta}{D^2} \tag{4}$$

where δ is the displacement of the pipe wall.

The inertia force can be written as

$$F_{in} = ma = (\pi t l D \rho)a \tag{5}$$

where m is the mass, a is the acceleration, and ρ is the mass density of the pipe. From Eqs. 4 and 5 the pressure fluctuations dp can be expressed as

$$dp = p_{el} + p_{in} = \frac{4tE\delta}{D^2} + t\rho a \tag{6}$$

and thus the correlation between pressure variations and pipe wall acceleration becomes readily available. Further assuming:

$$\delta = \delta_0 \sin(\omega t) \tag{7}$$

Eq. 6 can be rewritten:

$$dp = \left(\rho - \frac{4E}{D^2\omega^2}\right) ta \tag{8}$$

and the correlation is even more apparent. Another simple approach is to simulate the piping system as one dimensional beam model. Evans et al. (2004) took this approach and derived Eq. 9:

$$dp = -\frac{A\gamma}{g}a \tag{9}$$

where g gravitational acceleration, A cross sectional area of the beam and γ specific weight of the beam. Eq. 9 again indicates that the acceleration of the pipe is proportional to the pressure fluctuations in the fluid. As seen from the above equations, analytical calculations, which are based on different simplifying assumptions and theoretical models, can be derived and can serve as a first basis in describing pipe vibrations due to pressure fluctuations in a pipeline system. However, in its full detail, this phenomenon is very complex and requires use of experimental and more sophisticated analytical/numerical investigation.

In this background, we emphasize the use of acceleration data measured on the pipe surface as a measure of pipeline health. This study relies on the hypothesis that rupture of considerable size in the system causes sudden expulsion of water, resulting in abrupt change in force on the pipe internal wall to enhance the vibration of the system. Thus, a ruptured segment of the integrated system is expected to show a distinctly different transient response compared to the response associated with other common ambient forces.

4. WIRELESS SENSING PLATFORM

4.1 Existing Systems

Wireless platforms can be roughly classified into three types: real-time monitoring, data logging, and event-detection. The first is required to send the measured data immediately after the event, while the second aims to collect data for later analysis, and the third can be either. The proposed sensor technology provides a platform with near-real-time monitoring system for wireless data acquisition, transmission, processing, analysis and decision making. The challenges to designing a real-time monitoring system are fast communication links, fair and efficient media access control (MAC) protocols, and low-latency routing protocols.

Several wireless sensor platforms such as Imote, Mica2, and Tmote can all be used, assuming they are interfaced with the right sensor modules. Sensor modules vary depending on the application and technique. For instance, medium to large-sized leakage detection may use time-synchronized pressure and velocity (flow) data (Stoianov et al. 2003); sewer line monitoring may require hydraulic and water quality sensors as well as combined sewer outflows (CSO) (Stoianov et al. 2006); pipe failure detection may use acoustic/vibration sensors, velocity (flow) sensors, and pressure sensors for measuring transient (Stoianov et al. 2007). Pipe leakage may use barometric pressure sensors (Bakar et al. 2007) or acoustic sensors (Jin and Eydgahi 2008). However, the choice of the platform depends on many factors, including power and latency constraints, data rate, and local processing demand.

For real deployments, our PipeTECT system uses wired connection from sensor modules underground to the long-range radio above ground. For the purpose of our proof of concept in this paper, however, we chose the ultra-compact wireless sensor platform called Eco, as described next.

4.2 Eco Wireless Sensor Platform

The Eco platform is composed of one base station serving up to 50 Eco nodes to support the proposed real-time monitoring damage localization methodology (Chen and Chou 2008). The components of the Eco platform are shown in Table 1.

4.2.1 Eco

The Eco node is ultra-compact, low power, low cost, and suitable for dense deployment with a short wireless range (Chou (2010)). With the dimension of $13 \times 11 \times 7$ mm^3 including 40 mAh Li-polymer battery, Eco is one of the world's smallest wireless sensor nodes to date, as shown in Fig. 5. It is equipped with a triaxial accelerometer, a chip antenna, a temperature sensor, an infrared sensor, and a flex-PCB expansion port. It consumes less than 60 mW maximum. The Eco node consists of five subsystems: MCU, radio, sensors, power, and expansion port. The MCU (microcontroller unit) on the Eco node is the nRF24E1, which has an integrated 2.4 GHz RF transceiver with a data rate of up to 1 Mbps. The communication distance is up to 10 m. These features enable it to acquire data on a real-time basis. The triaxial acceleration sensor (Hitachi-Metals H34C) has a $\pm$3g range and temperature from 0-75°C. In addition, we can not only update the firmware of Eco remotely but also program many separate nodes at once (Chen 2008).

Thanks to its ultra-compact size and low power consumption, Eco nodes can be applied to many kinds of scenarios, including medical diagnosis, environmental and structural-health monitoring, and new human-computer interface. We take advantage of their characteristics and deploy multiple Eco nodes at the joints of a water distribution network to find the damage location for several reasons. First, it is small and self-contained, making it easy and minimally intrusive to deploy. Since we have built a large number of these units for another project, they are ready to use and our unit cost is low. Second, it has a high data rate of 1 Mbps, to be upgraded to 2 Mbps in the next version. This is in contrast to 19.2 kbps to 250 kbps for the most popular motes. Although more local processing can dramatically reduce the bandwidth demand, high-speed radio occupies the frequency band for a shorter amount of time to transmit the same amount of data. This means it will be more scalable to a large number of nodes with less contention among nodes. As with any wireless protocol, packet loss is inevitable and varies under different conditions. We observed a packet loss rate of under 5%.

Table 1. The specification of Eco and Base station

	Eco (Park and Chou 2006)	Base Station (Chen and Chou 2008)
Size (mm^3)	$13 \times 11 \times 8$	$76.2 \times 114.3 \times 31.7$
Sensor	Triaxial accelerometer ±3g (H34C)	None
	temperature sensor, infrared sensor	
Power Consumption	60 mW	900 mW
Max. Air Data Rate	1 Mbps	2 Mbps
Power Supply	40mAh Li-Polymer (3.7V) batt.	DC 500 mA (3.3V)
Wired Interface	Serial, SPI	10/100 base/T Ethernet
Wireless Interface	2.4 GHz Shockburst	2.4 GHz Enhanced Shockburst
Radio Range (m)	10 ∼ 20	10 ∼ 20
Cost	US$30 (@Qty 1000)	US$100 (@Qty 1)

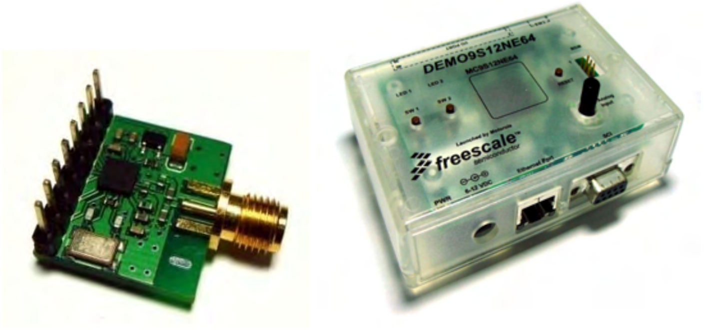

(a) 2.4 GHz RF Module (b) Microcontroller Board

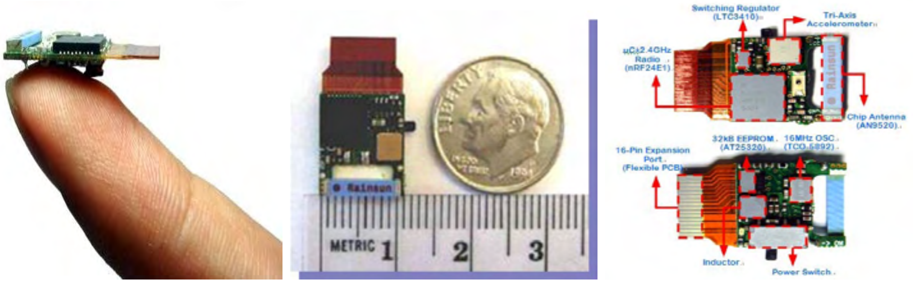
Figure 4. Photos of Base Station

4.2.2 Ethernet Base Station

The Ethernet Base Station is the unit that enables communication between the computer and Eco nodes. The base station connects to the host PC via 10/100 Mbps wired Ethernet interface. Fig. 4 shows the picture of the base station hardware. It consists of two modules: microcontroller board and 2.4 GHz RF module. The microcontroller board has a 10/100 Mbps Ethernet port, RS-232 port, 40 general-purpose I/O pins, and SPI for the connection to 2.4 GHz RF module. One base station can aggregate data from up to 50 Eco nodes using a low-complexity, high throughput multiple-access wireless protocol based on the concept of pulling (Yoo, Chen, and Chou 2009). A base station may pull autonomously or may be transparent to the host by passing commands and data through. Depending on commands, sensor nodes can send multiple replies for a single command. The pulling commands also effectively serve as a centralized time synchronization mechanism on the Eco nodes with a ±1 ms accuracy.

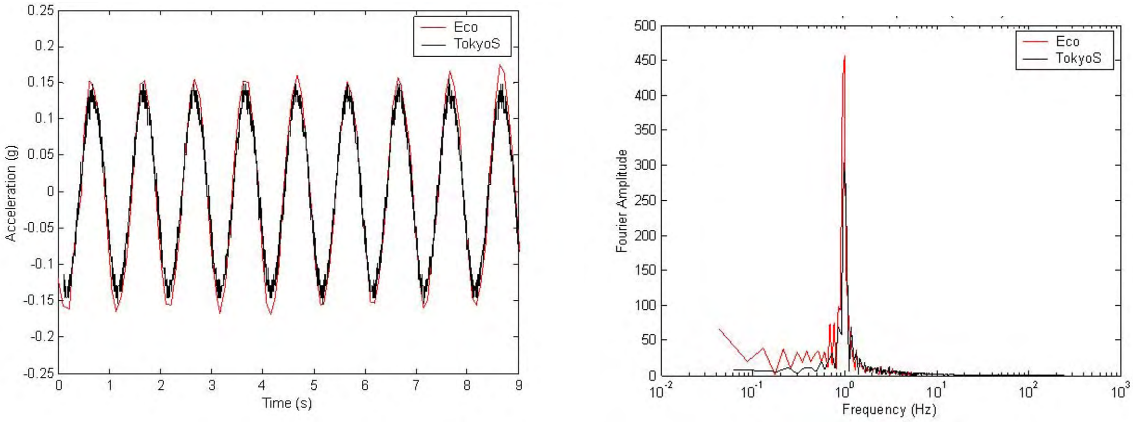
4.3 Calibration Test

To evaluate the performance of Eco, we conduct a lab experiment employing a shake table. Specifically, this experiment has been carried out at the low frequency of the shake table (1 Hz) to show the possibility of applying to structural-health monitoring. Eco and a traditional high-precision piezoelectric accelerometer, model #AS-3257 from Tokyo Sokusin, were both installed on the shake table to measure the vibration. Fig. 6 shows the time-histories and the FFT (Fast Fourier Transfer) results from Eco and the AS-3257 were nearly identical to each other. The FFT was carried out using standard Cooley-Tukey Fast Fourier Transform algorithm (Cooley and Tukey 1965). Herein, we carried out the FFT using standard Matlab 7 command. The number of FFT data points was 1024. The sam-



(a) On the finger (b) Eco Size (c) Top/Bottom View

Figure 5. Photos of the Eco Wireless Sensor Node.



(a) Time Domain Histories (@1 Hz) (b) Fourier Amplitude Spectrum (@1 Hz)

Figure 6. Eco Lab Validation Test: Comparison with Tokyo Sokusin #AS-3257 Accelerometer

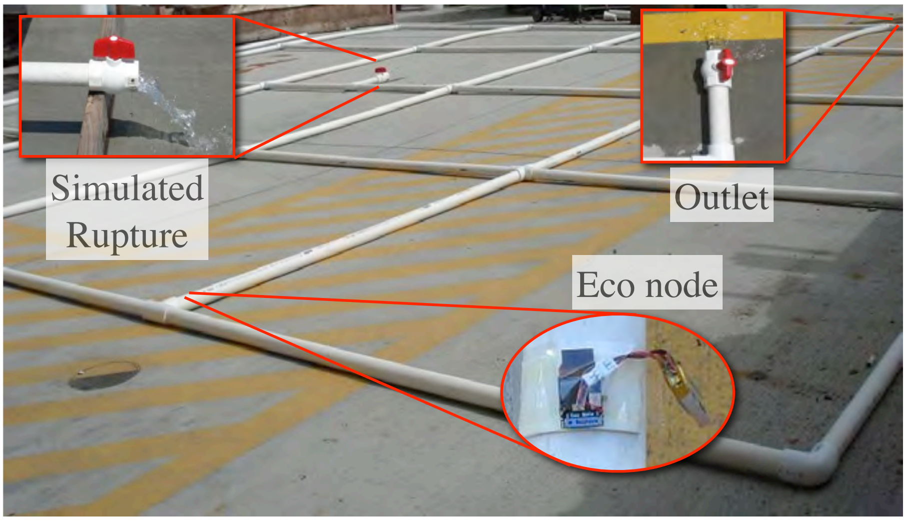
pling frequency was 125 samples/sec. The leakage will be handled by a smoothing technique using standard spectral window function such as Hann window.

5. PRELIMINARY EXPERIMENTS

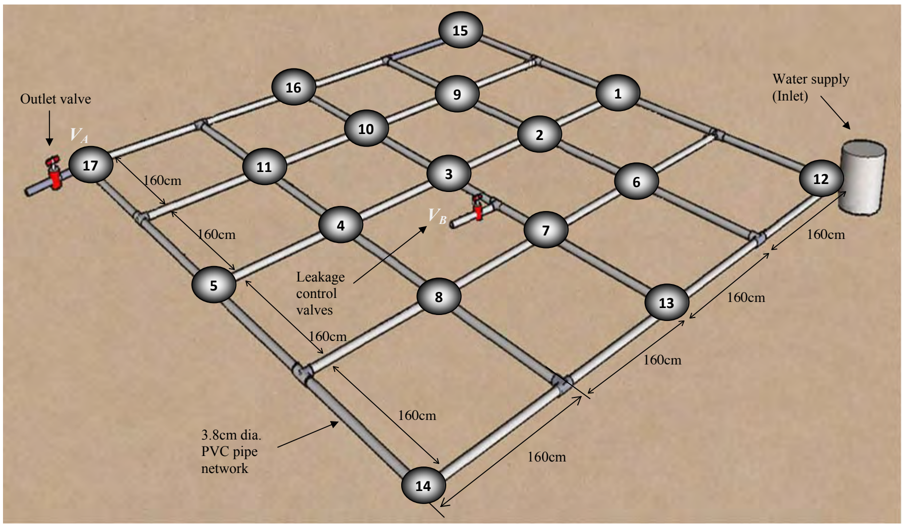
5.1 Experimental Setup

To validate the concept for noninvasive acceleration-based damage detection and assessment method of water distribution system using a wireless MEMS sensor network, a miniature water distribution system was constructed with 40 PVC pipes of 1.5-inch (3.8 cm) diameter with two valves labeled A and B. Fig. 7(a) shows the photo of this small-scale model, while Fig. 7(b) shows the overall size of this model to be about 600×600 cm^2, where valves A and B are used to control water pressure inside the water distribution system and to emulate a rupture, respectively. Valve A can be adjusted manually to three states: closing, half-opening, and complete opening, where closing means high pressure and no water flow; half-opening means medium pressure with water flowing in the pipe network; and complete opening means low pressure with water flowing. The half-opening case is similar to real water distribution system with ambient noise. Initially, both valves are closed to allow the pressure to build up gradually, and then valve A is opened by half. This procedure can provide not only a semi-steady-state water pressure inside the pipe network but also an ambient noise due to water flowing inside the pipe. Recording of the data begins after the water distribution system has been injected water and reached steady state, and recording stops a few seconds after valve B has been abruptly forced open completely to simulate a pipe rupture.

Eco nodes are installed at 17 joint points on the water distribution system to collect vibration data in real-time, as shown in Fig. 7(b). The data is wirelessly transmitted continuously to a host computer



(a) Photo



(b) Dimensions of Network and Locations of 17 sensors

Figure 7. Small-Scale Water Distribution System.

via a base station in near real-time, with about 1 second of lag.

5.2 Results and Analysis

Fig. 8 shows the measured data of rapidly changed acceleration using an Eco-based MEMS sensor network. Each Eco node is equipped with a triaxial accelerometer, and 17 nodes with three channels each successfully transmitted acceleration at 125 samples per second in real time to a laptop computer. A sequence of Z-direction acceleration records is plotted in Fig. 8.

We plot representative acceleration data from eight of the 17 joints, and they are labeled 1, 3, 7, 8, 11, 13, 15, and 16. These plots show that the effect of simulated rupture measured in terms of the magnitude (intensity) of acceleration depends on the distance between the rupture location and the sensor locations. For example, Figs. 8(a) and (b) show two representative acceleration data measured on the segment of rupture; (c) and (d) show those measured one segment away from the rupture point; (e) and (f) are those two segment away; and (g) and (h) are those one and two diagonals away, respectively. The sharp change of acceleration in each chart corresponds to the event of opening valve B.

Upon closer examination of Fig. 8, we find that the amplitude of each peak is different. The accelerations at joints 3 and 7 on the rupture segment are 2g and 1.9g, respectively. At one segment away (joints 8 and 13), they are 1.27g and 0.73g, and at two segments away (joints 1 and 16), they are 0.47g and 0.72g. This reveals that the acceleration change (which is almost equal to the acceleration itself because the ambient acceleration is negligibly small) is (locally) largest at the two ends of the ruptured segment. The magnitude of the acceleration change decreases as one moves away from the rupture point in distance as shown in Fig. 7(a) . Using these experimental results, we can plot a contour map for the convenience of visualization as shown in Fig. 9, which corresponds to the contour map in Fig. 1. The simulated damage in this case is located in the innermost and smallest polygon. These experimental results confirm that the proposed method is promising in that the change in the pipe surface acceleration can be used as metric to develop the contour map from which the location and extent of pipe damage can be identified.

6. CONCLUSIONS AND FUTURE WORK

We propose a novel water-pipe damage detection method based on time-correlated acceleration data collected using a wireless MEMS-sensor network from different joints of a water distribution system. Each sensor measures the acceleration change on the pipe surface non-invasively to determine rupture events and to locate the point of rupture. The results of the preliminary experiment validate the concept of measurement of pipe acceleration for damage detection. To enhance the accuracy of detecting damage location in a larger-scale water distribution system, many improvements are needed. For time synchronization, a distributed scheme using WWVB (atomic time broadcast) and GPS are being evaluated. The centralized wireless communication protocol will also be replaced with a more distributed scheme and relaying capability to handle the much longer expected range. We are also evaluating better algorithms for data analysis, including the possible use of frequency-domain analysis. Further study is needed to correctly analyze the situations in sharp bends and T-joints and to understand the pipe vibration under the ambient and transient hydraulic conditions. We plan to install a new platform with greatly enhanced wireless communication capabilities on a subset of a regional water supply network such as the City of Westminster and the Irvine Ranch Water District, where their existing SCADA measurements can be used for possible comparison.

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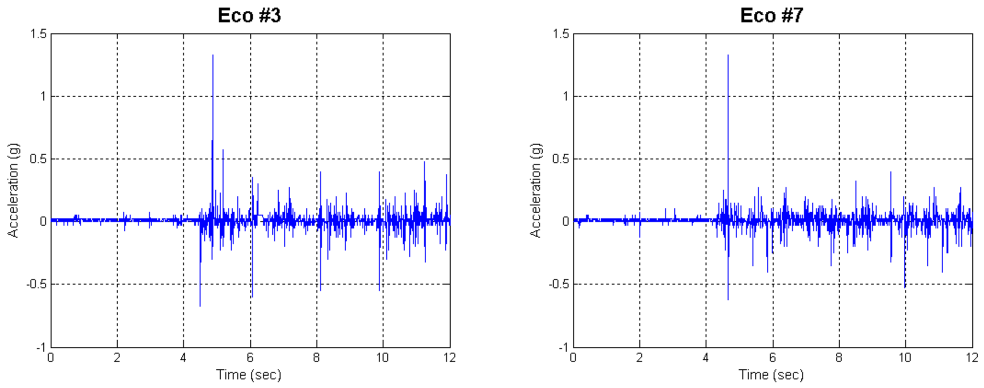
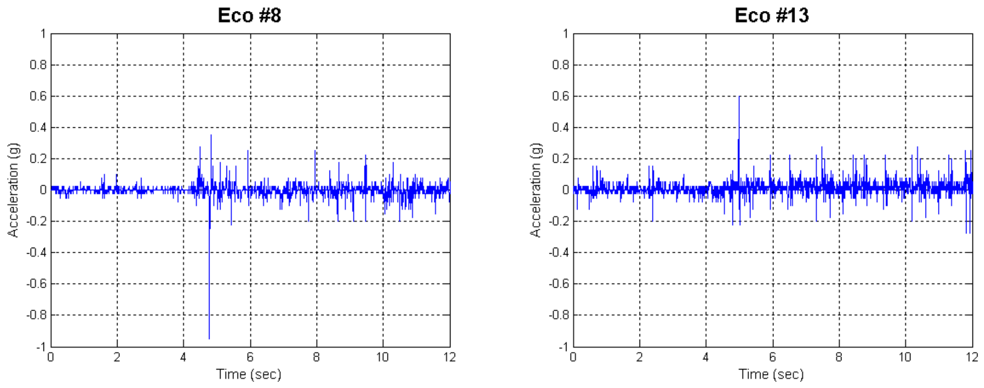
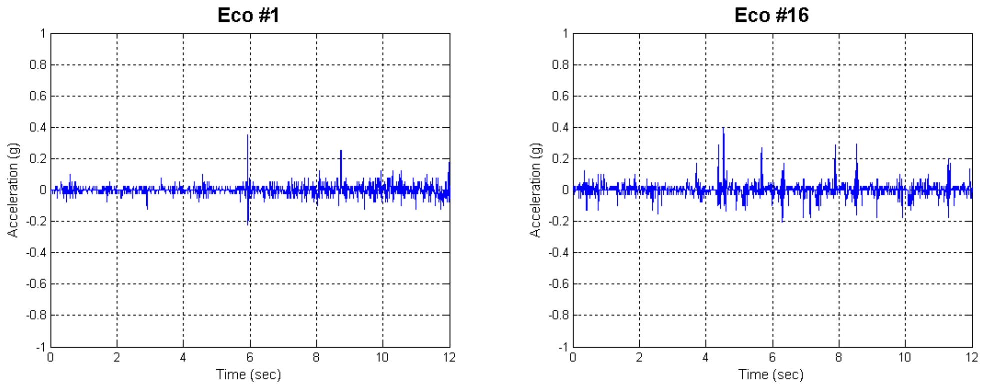


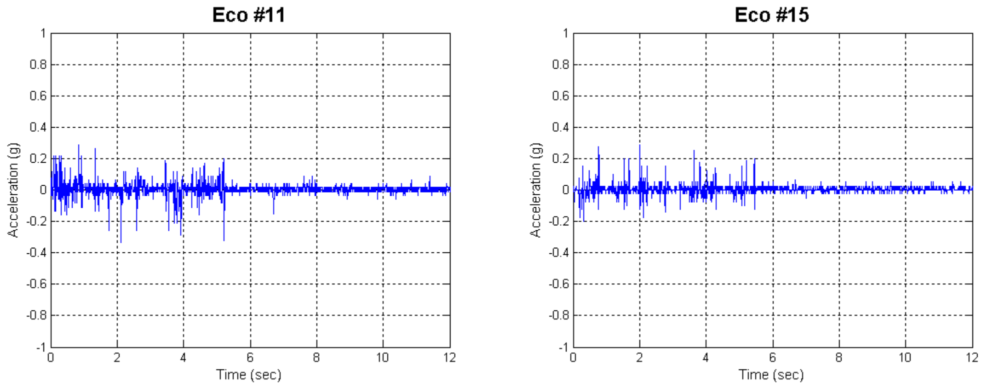
(a) Rupture segment(left) (b) Rupture segment(right)



(c) One segment away(lower) (d) One segment away (right)

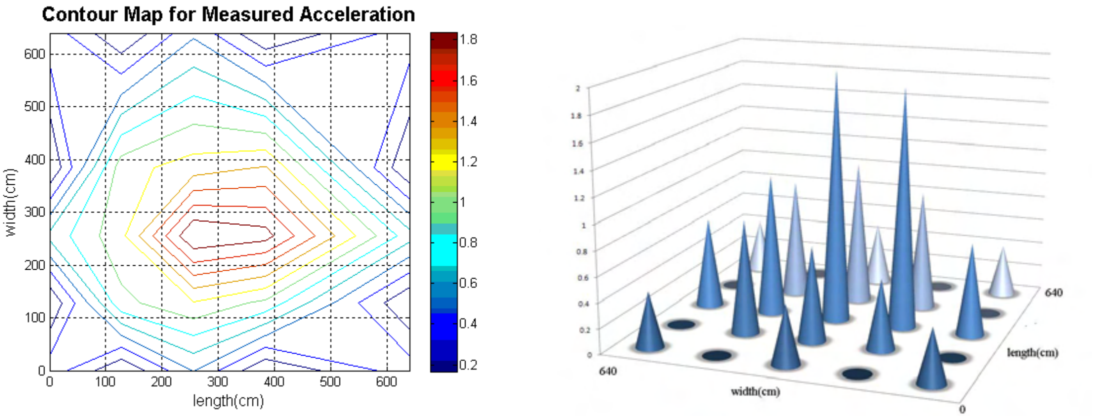


(e) Two segment away (upper) (f) Two segment away (left)



(g) One diagonal away (h) Two diagonals away

Figure 8. Acceleration Data measured by Eco nodes



(a) 2D Contour Map (b) Visualization of measure acceleration data

Figure 9. Simulation results for a miniature water distribution system.

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Response to Reviewer Comments

The authors thank the reviewers for the second round of reviews.

Response to Reviewer #1

C: *The original comments have been carefully addressed in the author's response; however some of the answers are not found in the revised paper. For example, in the response, the author describes data loss at approximately 5% in the experiments but this is not discussed in the manuscript.*

A: This was added to the end of the Eco section.

C: *In the "Conclusions and Future Work" some system limitations are mentioned as items to address in the future but their existing performance levels are not presented in the experimental results. This is true of both communication performance and time synchronization."*

A: We revised the conclusion to clarify these points. Basically Eco relies on a centralized time sync and communication scheme for simplicity, but for real deployment they will be more distributed and make use of relays to cover a longer range.

C: *When citing references in the text with more than two authors, it is adequate to cite the references as (Author 1 et al. Year) or Author 1 et al. (Year), rather than listing all authors in the text.*

A: These have been reformatted.

Response to Reviewer #2

C: *In the revised paper, the original comments have been carefully addressed. However, the many of the answers given in the rebuttal statement have not been stated in the paper. The paper is publishable in the journal, but the address of the following comments will enhance the paper.*

1. In Section 2.1, no need to list the authors' name in the format of the journal.

A: All of these have been reformatted.

C: *2. Section needs to be divided according to the used methods: Section 2 for damage detection using hydraulic transient (equals to water head gradient) (conventional and invasive way) and Section 3 for damage detection using acceleration gradient.*

A: (I am not sure if I understand this comment – does it mean to change the title headings? Please check if I change them correctly.)

C: *3. State the official site of Eco mote and its description in the paper to help readers understand the details of Eco mote.*

A: The official website has been added to the references and cited in the Eco section. The same paragraph actually already contains details including all of the components used and their specifications.

C: *4. Make section 4.2.3 to describe the calibration test of Eco in more detail (stated in the rebuttal statement): i.e., 1) how the FFT was carried out, 2) how many data used, 3) what was the sampling frequency, and 4) why the leakage is shown in the figure and how it will be handled later. It is confusing that calibration part is included in Section 4.2.2 Base station.*

A: The paragraph following the base station description is now in a new subsection, with additional detail filled in.

C: *5. Tokyo Sokusin is not the model name of the accelerometer, but the manufacturer. Write exact model name of wired accelerometer used in the calibration test.*

A: Servo accelerometer, Model # AS-3257. This has been put into the text.

C: *6. The part describing how the pipe rupture was modeled in the test (shown in last sentence of the first paragraph of Section 5.2) can be moved to Section 5.1 Experimental Setup.*

A: Yes, we moved the text.

C: *7. Enlarge the pictures of installed Eco motes, Water Outlet, and Rupture (Fig. 7(a)).*

A: The nested photos have been enlarged.

C: *8. Mark the coordinate in Fig. 7(b) to help readers understand the direction used in the test. And more detailed dimension in Fig. 7(b) is also required (Hard to know whether it is squared lattice shape or rectangular.*

A: The detailed dimensions have been added.

C: *9. The last paragraph of Section 5 needs to be moved in the adequate section. The first and second sentences can be moved to Section 5.1, and the third and last sentences to Section 5.2.*

A: Yes. we thank the reviewer for such careful editing comments. We actually decided to move both to Section 5.1, although to different locations to make it flow better.