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Design and Implementation of Leak Acoustic Signal Correlator for Water Pipelines

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Abstract: It has been estimated that more than 20% of water supply is being lost due to leakage. In order to promptly find out the leakage from water pipelines, the paper proposes a complete solution of leak acoustic signal correlator for leak detection. When leakage occurs, leak acoustic signals would propagate along the wall of water pipelines which are usually strong correlation. Cross-correlation algorithm is relatively effective for leak detection. And it is often conducted to analyze leak acoustic signals, picked up at both sides of a leak, to determine the position of leak. Based on the principle of leak detection, a set of leak acoustic signal correlator has been designed and implemented, including key parameters selection, circuit design and software development. Key parameters have been determined to ensure the positioning precision and detection distance of leak acoustic signal correlator. Meanwhile in order to satisfy the demands of real-time processing, the architecture of signal processor employs DSP+FPGA as its dual-core. Related tests shows the solution proposed in this paper could be adapted to different occasions of leakage by changing parameters which could also be upgraded as a platform for further study.

Key words: Leak detection, cross-correlation algorithm, circuit design, software development

INTRODUCTION

It has been estimated that more than 20% of water supply is being lost in the world due to leakage. Water resources loss and geological disasters are caused by leakage from buried pipelines (Thornton *et al.*, 2008; Folkman *et al.*, 2012). Therefore, discover, position, repair and eliminate the potential hazards caused by water leakage have great significance. Leak detection equipment has been through 3 stages of development (Yang *et al.*, 2008; Geiger, 2006). Initially, listening rods were placed directly on the wall of the pipelines or their appurtenances, such as fire hydrants and valves, to detect the leak sound (Yang *et al.*, 2008; Hunaidi and Chu, 1999). However, listening rods were gradually replaced by ground microphones, as listening rods could not detect those sounds propagated in buried pipelines. In order to pinpoint underground leakage, ground microphones were usually deployed on pavements where above those buried pipelines (Yang *et al.*, 2008; Cataldo *et al.*, 2012). While the investigation depth of ground microphones mainly depended on their sensitivity (Gao *et al.*, 2005). At present, the state-of-the-art leak detection instrument is leak acoustic signal correlator which wins greater favor as its high positioning accuracy, deep investigation depth and independence of users' experience (Gao *et al.*, 2009; Zhang *et al.*, 2009).

When leak occurs, water erupts from pipelines and there will be a turbulent jet in leak pipelines. As the jet hits against the wall of pipelines it will carry significant turbulent pressure fluctuations which will impact on the pipeline to generate leak acoustic signal which will propagate along the wall of pipeline (Yang *et al.*, 2008; Muggleton and Yan, 2013). When pipeline pressure is constant, frequency content of leak acoustic signal is influenced seriously by pipeline material. Specifically frequency content gets lower as pipeline material becomes softer. The half power bandwidth of metal pipeline mainly concentrates on 500~1500 Hz, while it distributes from 300-1000 Hz when leak occurs at plastic pipeline (Zhang *et al.*, 2009; Zhang and Guo, 2011). There is a cutoff frequency as leak acoustic signal along the wall of pipeline by Wang (2005) and it can be estimated by:

$$f_B = \frac{1.84c}{2\pi\varphi} \tag{1}$$

where, c is sound speed in the pipeline, φ is the radius of the pipeline.

In Table 1, the empirical values of sound speed at different pipelines are presented. It is clear from Table 1 that sound speed, determining the positioning precision

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Table 1: Empirical values of sound speed in different pipelines

Diameter (mm)	Cast-iron pipe ($m\ sec^{-1}$)	Steel pipe ($m\ sec^{-1}$)	Cement pipe ($m\ sec^{-1}$)
100	1220	-	-
150	1170	-	-
200	1120	-	-
250	1080	-	-
300	1010	1070	1080
500	1000	1030	1020
600	1000	990	980
800	980	960	970
1000	980	930	960
1200	980	920	960

of leak acoustic signal correlator Wang (2005), is seriously influenced by pipeline material, especially when the radius is small.

Take cast-iron pipe as an example to analyze the cutoff frequency of pipelines which has been widely used as water pipelines. It is indicated in Table 1 that sound speed generally does not exceed 1000 m sec^{-1} when the diameter is more than 300 mm, therefore, the cutoff frequency is:

$$f_B = \frac{1.84\times1000}{2\times3.14\times0.15} \approx 1953.0\text{Hz} \tag{2}$$

Therefore, leak acoustic signal could propagate along the wall of pipeline which provides the possibility for leak detection of water pipelines. In this paper, a complete solution of leak acoustic signal correlator is proposed. First, key parameters have been determined to ensure the positioning precision and detection distance. Then the complete solution is stated, including circuit design and software development. Finally related tests are carried out, to embody the total performance of leak acoustic signal correlator.

LEAK DETECTION AND LOCALIZATION BASED ON CROSS-CORRELATED ALGORITHM

The cross-correlation algorithm is relatively effective for leak detection (Yang *et al*., 2008). Sensors are located on both sides of a leak to pick up acoustic signals. The signals are carried into a correlator which conducts the cross-correlation function of these signals and then sends the result to a processor (Gao *et al*., 2009). Fig. 1 depicts a typical measurement arrangement for leak detection and localization based on cross-correlation algorithm. An access point where a sensor can be attached is located on each side of the leak at distances L_A and L_B. The distance of sensor A and B is L. If it is assumed that the propagation wave speed is c and Δt is the time delay which provides an estimate of the time delay. Referring to Fig. 1 it is given by:

$$\begin{cases} L_A + L_B = L \\ \dfrac{L_A - L_B}{c} = \Delta t \end{cases} \tag{3}$$

The position of the leak is given by:

$$L_A = \frac{L + \Delta t \cdot c}{2} \tag{4}$$

Detection distance and positioning accuracy: It is assumed that sampling frequency is f_s and sampling points is N and Δt can be expressed as:

$$\Delta t = \frac{N}{f_s} \tag{5}$$

As the leak point between the two sensors, so:

$$\Delta t.c \le L \tag{6}$$

Combine Eq. 5 with Eq. 6:

$$\frac{N}{f_s} \le \frac{L}{c} \tag{7}$$

It is clear from Eq. 7 that detection distance changes with sampling frequency if the number of sampling points is fixed. Generally just considering the lowest sampling frequency, the system gets the longest detecting distance. As the maximum frequency of leak acoustic signal is usual less than 2000 Hz, therefore, Nyquist frequency should be 4000 Hz. In order to obtain higher positioning accuracy, sampling frequency is set as 10 kHz. Considering the situation that sound speed c = 1000 m sec^{-1} and the correlation peak occurs at the 1024th sampling point, the detection distance is given by:

$$s = \Delta t \cdot c = \frac{1024}{10\times10^3}\times1000 = 102.4\ \text{m}$$

Therefore, detection distance is 102.4 m which can satisfy the engineering requirement. Positioning accuracy p is defined as:

$$p = \frac{s}{N} \tag{8}$$

Combine s = Δt.c with Eq. 5, p is given by:

$$p = \frac{c}{f_s} = \frac{1000}{10\times10^3} = 0.1\text{m}$$

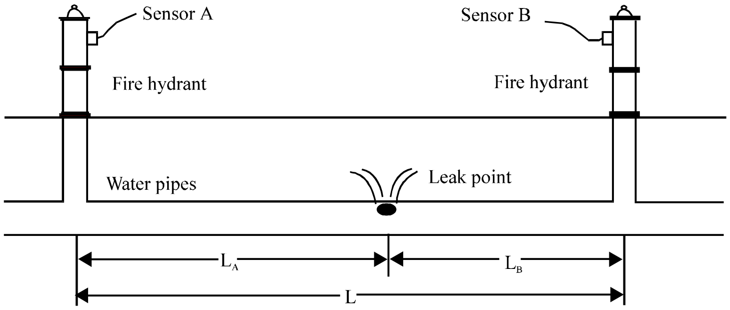

Fig. 1: Schematic of leak detection and localization based on cross-correlation algorithm

Therefore, positioning accuracy is 0.1 m which can satisfy the requirement.

The above analysis for positioning accuracy is at ideal situation, but in fact positioning accuracy is influenced by ambient noise, sampling frequency and synchronization of system.

Influence of ambient noise on positioning accuracy: In actual engineering, ambient noise and electrical noise always influence positioning accuracy which results in the decline of positioning accuracy. If it is assumed that ambient noise is additive white Gaussian noise and the signal average power is defined as:

$$\bar{P} = \frac{1}{N}\sum_{n=0}^{N-1}(x(n))^2 \tag{9}$$

And the signal-to-noise ratio is given by:

$$SNR = 10\lg\frac{\bar{P}_s}{\bar{P}_n} \tag{10}$$

With the reduction of SNR, the correlation peak is away from the real time delay and positioning accuracy will decrease.

Influence of sampling frequency on time delay error: There is a close relationship among sampling frequency, the number of sampling point and detection distance in leak detection. Specifically, if the sampling frequency gets higher, the sampling points would become more, the time delay error would decrease and the positioning accuracy would be increased. The relationship between fs and Δt is given by:

$$d = \frac{c}{f_s} \tag{11}$$

where, Δd is the error which provides an estimate of positioning accuracy.

Table 2: Influence of sampling frequency on time delay error

fs (kHz)	6	8	10	12	14
Δd (m)	0.167	0.125	0.100	0.083	0.071

It is assumed that L = 102.4 m, c = 1000 m/c and the influence of sampling frequency on time delay error is given in Table 2. It is clear from Table 2 that Δd decreases with the increasement of sampling frequency. When fs = 14 kHz, Δd is only 0.071 m which is beneficial for positioning precision. However, higher sampling frequency would bring heavy burden for hardware of leak acoustic signal correlator. Meanwhile, in order to reduce the complexity of software development, the number of sampling point is wished to be fixed. Further more, the detection distance gets shorter when sampling frequency becomes higher based on Eq. 7. Based on the above analysis, sampling frequency is set as 10 kHz.

Influence of synchronization on positioning accuracy: Positioning accuracy depends on the accuracy of time delay Δd, so it is relatively strict for the synchronization of signal acquisition. The higher positioning accuracy can be gotten only if signal acquisition at the same time.

Wireless module has many drawbacks such as low transmission rate (maximum 19200 bps) and a byte time delay either receiving or transmitting. Due to the limitation, transmission rate up to 19200 bps and a byte time delay, 1ms is necessary to transmit a control command. It is unable to accept for the positioning accuracy.

In the paper, utilize FPGA to control the wireless modules and two identical transceiver modules are designed on FPGA. As the two modules don't influence each other in operation, FPGA can control the system to collect data at the same time.

LEAK ACOUSTIC SIGNAL CORRELATOR FOR WATER PIPELINES

Circuit design: Leak acoustic signal correlator consists of sensors, signal acquisition unit and signal processing unit. The schematic of leak acoustic signal correlator is shown in Fig. 2. Sensors are positioned on both sides of a leak point to collect vibration acoustics. It is clear that the performance of sensor will be of great significance to localization result. Piezoelectric accelerometers are the best choice to pick up vibration acoustics which is related with the characteristics of vibration acoustics (Gao *et al*., 2009). The signal acquisition unit collects data from leak pipelines and sends the data by a wireless module; the signal processing unit receives the data and carries correlation algorithm out; the position information (the distance from the leak point to one sensor) of leakage will be displayed on LCD immediately.

To enhance SNR at the initial stage of signal, the output of each sensor is routed to signal conditioning circuit which includes low-pass filter and signal amplifying circuit. The design of Impedance Matching, Low-pass Filter and Manual Gain Control (MGC) can make data acquisition achieve optimal SNR. This in turn will highly improve the accuracy.

The signal processing unit including FPGA+DSP has flexible structure, brevity-developing period, easy maintenance and expandability and fits for modularization design. On the basis of the architecture of FPGA+DSP, hi-speed real-time signal processing is achieved. Applying this architecture is based on the following considerations:

- Use FPGA to realize data acquisition, buffering and synchronization of system. It is the big difference compared with other designs
- DSP will be disentangled from other work and focus on compute
- The structure is very flexible and developing period will be shorted
- Provide a powerful general-purpose platform for both new system designs and legacy system upgrades

Software development: According to the functional requirements, the software based on FPGA consists of the clock management module and data acquisition module based on SPI soft nuclear. In addition, the DSP correlation algorithm is conducted by calling for library functions in DSPLIB supplied by Texas Instruments. Finally the device drivers of keyboard and LCD panel are designed.

Generally, the execution of system software is consistent with the process of data transfers and the flowchart of system software is shown in Fig. 3. Reset operation is performed when the system powers on and the system enters the standby state. When one key is press down, MCU (Micro Control Unit) detects it and determines the function of the button. Then the statement of the pin which connects MCU and FPGA will change. FPGA realizes the change and controls the wireless module to send the introductions of signal acquisition. The unit of signal acquisition receives the introductions and begins to collect signal. After signal acquisition, the signal acquisition unit transmits data to the signal processing unit. Those data get stored into FIFO which lies in the internal of FPGA. If FIFO is half-full, DSP reads the data into data storage by it EMIF (External Memory Interface). Based on those data, correlation algorithm will be carried out and the position information of leak will be displayed on LCD immediately.

SYSTEM TESTS

Test results: In order to evaluate the performance of leak acoustic signal correlator, related tests have been carried out, such as Electrical Noise, Dynamic Range and Detection Distance. The results are as follows:

- **Electrical noise:** 8.16 μV
- **Dynamic range:** 0~90dB (MGC)

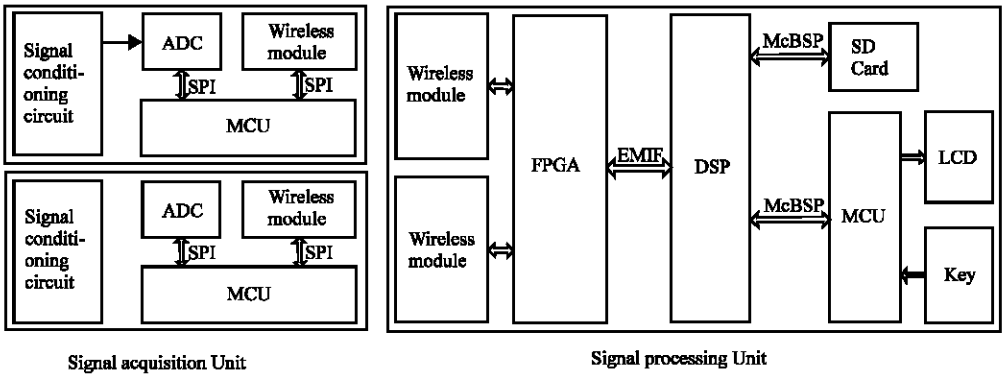

Fig. 2: Schematic of leak acoustic signal correlator

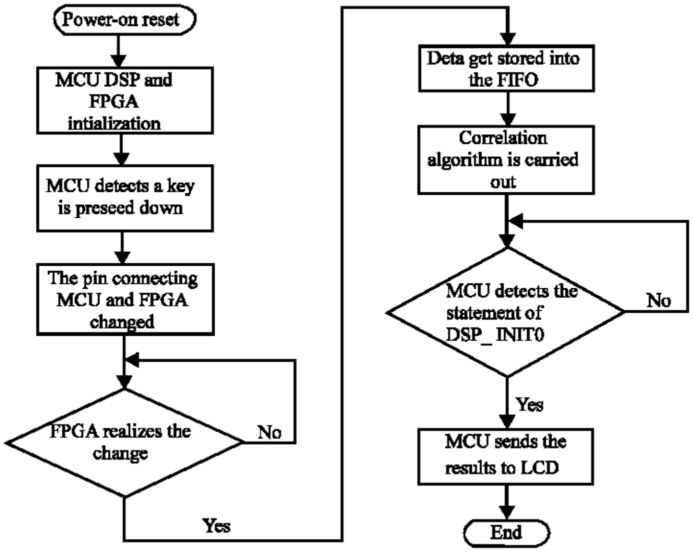

Fig. 3: System software flowchart

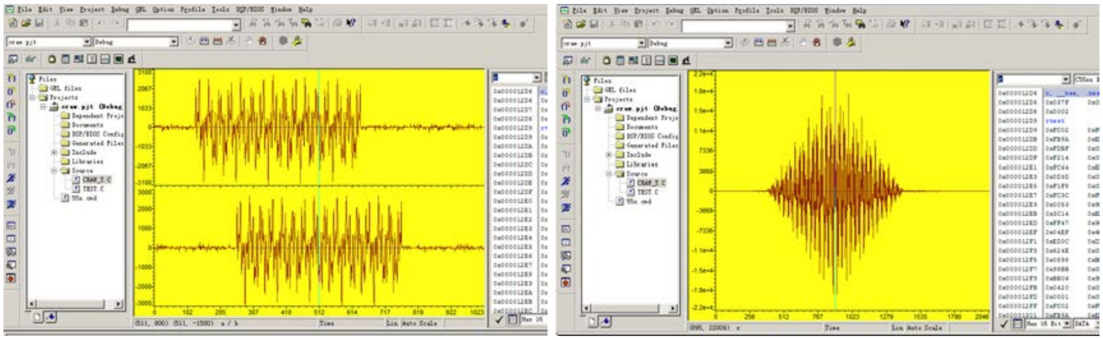
(a)
(b)

Fig. 4(a-b): Cross-correlation using constructed signals in DSP: (a) Two channel constructed signals (b) Cross-correlation using constructed signals

- **Detection distance:** 150 m (limited by transmitter power of wireless module)

Tests in laboratory: Construct two channel signals by MATLAB and then write the data into data storage area of the two signal acquisition units separately. The constructed signals are superimposed with 300, 1000 and 1800 Hz of sinusoidal signal, SIR = 0dB and fs = 10 kHz. Fig. 4 shows the constructed signals and the result of cross-correlation in CCS3.3.

Based on the result displayed on LCD, the delay time computed by DSP is consistent with that of the program written by MATLAB and the validity of design is proved. Statistical analysis results shows that the cross-correlation method provides the effective results for leak detection. However, such a technique has limited application due to identify the correlation peak location accurately. As one of the alternative methods, energy center convergence algorithm is widely used in detection systems.

CONCLUSION

As the many successes of research on leak detection of water pipelines in the past decades, a set of leak acoustic signal correlator is proposed in this paper. At first, acoustical characteristics of leak signals in water distribution pipelines is analyzed. In order to ensure the positioning accuracy and detection distance of system, theoretical analysis has been conducted. Based on theses analysis, design hardware platform. The platform including FPGA+DSP has flexible structure, brevity-developing period, easy maintenance and expandability and fits for modularization design. And then, system software is introduced. At last, related tests demonstrate that every part of the instrument works properly and the main performance index matches the design requirements.

In comparison with other solutions for leak detection, as described in literatures, the main advantages of the system are simple operation and high positioning accuracy. Meanwhile, the solution could be adapted to different occasions of leakage by changing parameters which could also be upgraded as a platform for further study.

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