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A Basic Experimental Study on Analysis of Leak Signal and Monitoring Method for Water Supply Pipe

Youngseok Kim [1], Haewook Jung [2,*], Jaesuk Ryou [3,*] and Jaehyuk Choi [4]

1 Daum Engineering Co. Ltd., Seongnam-si 13493, Korea; youngseok21c@hanmail.net
2 Woori Engineering Co. Ltd., Sejong-si 30054, Korea
3 Department of Civil & Environment Engineering, Hanyang University, Seoul 04763, Korea
4 Department of Mechanical Engineering, Sogang University, Seoul 04107, Korea; jhchoi@sogang.ac.kr
* Correspondence: ajussen1@naver.com (H.J.); jsryou@hanyang.ac.kr (J.R.)

Abstract: Water supply systems are essential elements for human life and industry, and water leaks and water supply cut-off may cause major problems. Local water leaks and pipe failures in the water supply system are inevitable problems due to the aging of pipes. Therefore, leakage detection and prevention are required to monitor the integrity of the water supply system. This paper is a fundamental study on the applicability of the smart bolt, which was developed as a monitoring system to detect water leakage in water supply monitoring. Detection experiments were conducted using a smart bolt with a built-in strain sensor and an accelerometer. Through finite element analysis using ANSYS 2019 R2 and tensile strength testing, the strength of the smart bolt was confirmed to have the acceptable tensile strength. The smart bolt used in this study was verified to meet the allowable criteria of torque and tensile stress for a municipal water supply system. The frequency responses of the simulated leakage pipe system, according to the leakage of the valve and the main pipe, were analyzed, and a leak signal at the valve leak point was detected in the 60-Hz band. The main pipe leaking point was observed to produce a leak signal with a much higher-order mode than that of the valve leak point. Therefore, the smart bolt can be applied to detect warning leak signs from water supply valves and to monitor for loosening of the bolts.

Keywords: leak detection; FFT analysis; water supply; monitoring; smart sensor

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1. Introduction

Water supply networks are the most important factors of municipal water supply facilities, but as most of them are buried underground, it is difficult to check for the damage and deterioration of the pipes [1]. Therefore, the amount of water leakage in water supply networks is increasing. In Europe, 6.5% to 24.6% of tap water is lost from the water supply network [2]. In South Korea, the leak rate of the water supply was found to be 682 million m^3 (10.5%) of the total water supply volume of 6492 million m^3 in 2017 [2]. It has been reported that water leakage occurs at the water supply lines and also in the valves. According to the results of a survey of large water supply pipes (diameters of 400 mm to <700 mm), 1% of the leaks (71 cases) were from valves [3].

The main causes of valve leakage are aging of the valve packing, poor connections during construction, and loosening of bolts due to continuous micro-vibration. When a valve problem occurs, it can lead to many complaints from the public due to widespread water supply cut-offs. Therefore, water leakage in valves as well as pipelines must be considered as the primary management target in the water supply maintenance system [4].

Current leak detection methods in water pipes are divided into three categories: software-based methods, conventional methods, and hardware-based methods [5]. Software-based methods use various types of computer software to analyze and detect leaks in pipeline systems [5]. This method is used to measure internal pipeline parameters including pressure, flow rate, and temperature [6–8]. These methods are precise and easy to use, but it is expensive and difficult to detect leak levels [5]. Conventional methods require experienced personnel who need to walk along a pipeline and look for unusual patterns near the pipeline based on odors or sounds due to a leak [5]. Hardware-based methods can detect leaks by visual observation or using appropriate measurement equipment [5]. Representatively, there are studies on vibration sensors, piezo sensors, bi-wire sensors, and ultrasonic sensors for a leak detection technique using vibration [9–11]. Most of these methods are low-cost and high-sensitivity leak detection, but it is difficult to find the leak point [5]. Acoustic emission sensors can estimate the leak point using the transmission rate of the leak sound [12]. However, the disadvantages of the acoustic method are the difficulty of placing acoustic sensors in the right location at the water pipeline and the difficulty in detecting quiet leaks, which generate no sound [12]. Due to this fact, researchers have shown a strong interest in the vibration technique for leakage detection [5,12].

Most of the previous studies have been on the detection of leaks in pipelines, but studies on leaks caused by the loosening bolts of valves are insufficient. Therefore, in this study, a smart bolt was developed as a monitoring system to continuously check the leak condition of the water supply valves. The smart bolt incorporates a strain sensor to detect loosening of the bolt by monitoring the tension of the bolt, and an acceleration sensor to check the leakage in the valve. Through fundamental experiments and analyses, we confirmed the applicability of the smart bolt for leak detection.

2. Theoretical Background

2.1. Coupled Vibration of Fluid and Pipe

In the vibration of the water supply pipe, waves transmitted in the longitudinal direction of the pipe and transverse waves transmitted in the out-of-plane direction are generated [13]. To measure the leak signal using an accelerometer sensor, out-of-plane vibration must be measured because it is related to the coupled vibration of the pipe [13].

The coupled vibration of the fluid and the pipe can appear in several modes, as shown in Figure 1. The basic forms of coupled vibration are the n = 0 'breathing mode' and n = 1 'bending mode' of the pipe. If the pipe is a single beam, it corresponds to the bending vibration of the single beam. In general, because water supply pipes are buried and constrained, it is difficult to detect a large-amplitude bending vibration. The n = 2 mode is the 'ovalling mode', which is mainly seen at high frequencies.

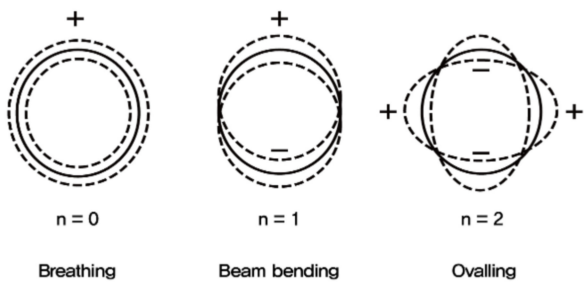


Figure 1. Coupled vibration modes of fluid and pipe.

Of these, the breathing mode (n = 0) is related to the transmission of fluid sound waves in the longitudinal direction. The fluid sound transmitted by a leak is a longitudinal wave whereas what is to be measured is the transverse vibration of the pipe [14,15].

When a strong leakage occurs at a buried water supply pipe, a leak signal with a wide frequency range is generated from the inside of the high-pressure pipe to the outside of the low-pressure pipe. Unlike temporary noise, the leak signal can be clearly distinguished because it continuously generates a signal when a leak occurs [16,17].

2.2. Fast Fourier Transform

The Fourier transform is an analysis method that decomposes a function (or signal) over time into a function over frequency components. The Fourier transform is expressed as Equation (1):

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \ (here, \int_{-\infty}^{\infty} |x(t)|dt < \infty) \quad (1)$$

If $x(t)$ is the 'impulse response' of a system, its Fourier transform, $X(f)$, becomes the frequency response of the system. As this Fourier transform takes considerable time to analyze, the supplemented method is a fast Fourier transform (FFT) [16].

In this study, we analyzed the frequency response of the acceleration signal measured from a smart bolt fixed to the valve to assess the characteristics of the leak signal and the performance of the smart bolt [18,19].

3. Development of the Smart Bolt

3.1. A Smart Bolt and Finite Element Analysis

In general, Fiber Bragg Grating (FBG) sensors, strain gauges, and piezoelectric sensors have been studied to monitor the joint bolt [20]. In this study, a form of inserting strain gauges in bolts was conceived as a method for monitoring the joint bolt. A 2-mm-diameter hole was drilled to a depth of 35 mm from the center of the head of an M16 80-mm high-tension bolt installed in the valve in the studied water supply pipe, as shown in Figure 2. An internal strain gauge (BTM-6C for steel; Tokyo Sokki Kenkyujo, Tokyo, Japan) was inserted into the hole and injected with epoxy. An acceleration sensor (3055D4; Dytran Instruments Inc., Chatsworth, CA, USA) was fixed to the smart bolt head. The specifications of sensors in the smart bolt are as follows (Table 1).

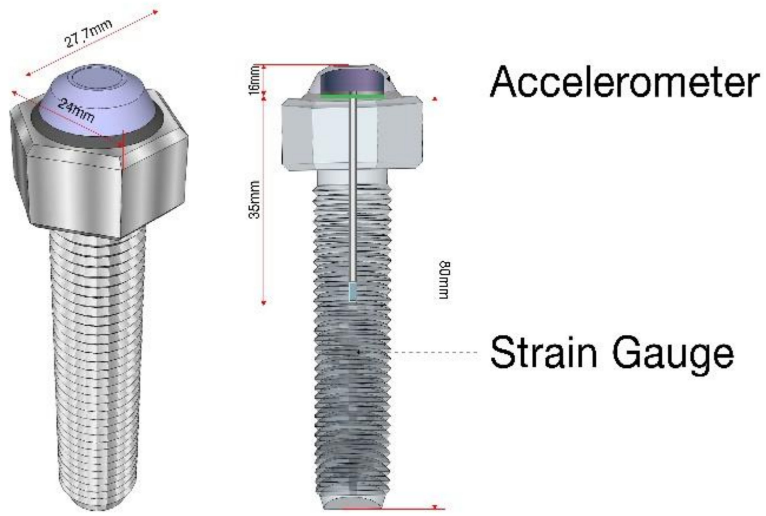
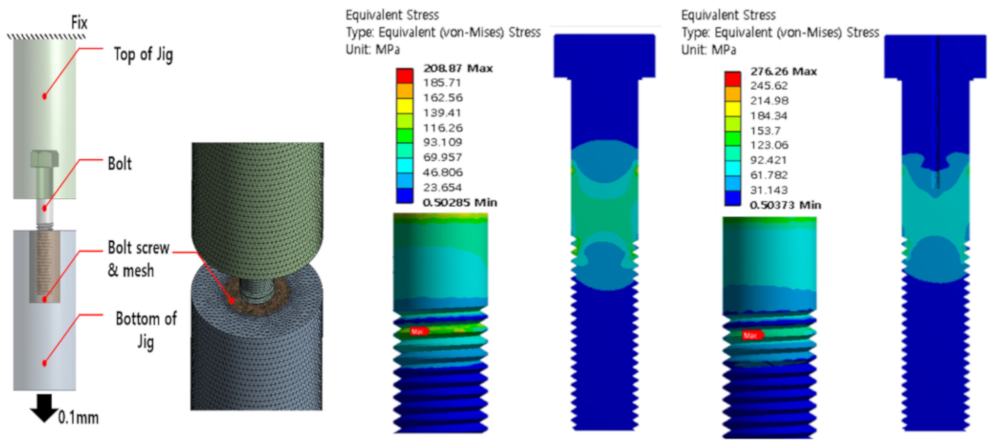


Figure 2. M16 80-mm smart bolt.

Table 1. Specifications of sensors in the smart bolt.

Type	Specification
Accelerometer (3055D4)	Frequency Response, ±10%: 1 to 10,000 Hz Sensitivity, ±5% [1]: 5 mV/m/s^2 Broadband resolution: 0.010 m/s^2 RMS
Strain gauge (BTM-6C)	Gauge length: 6 mm Gauge resistance: 120 ± 0.5 Ω Gauge factor: 2.14 ± %

Finite element analysis (FEA) is an analytical method generally used to evaluate a specific object under conditions that simulate the applied environment and is used in various fields [21,22]. In order to confirm the applicability of the smart bolt, FEA was conducted with ANSYS 2019 R2 to verify the integrity of the bolt depending on the presence or absence of a bolt hole for inserting a strain gauge. The physical properties of the bolt (SM45C carbon steel) are E = 250 Gpa, ν = 0.29, σy = 490 Mpa, and σu = 686 MPa. The bonding condition between the jig and the bolt is bounded, and the boundary condition of the top of the jig is fixed. After the finite element modeling, as shown in Figure 3, the von Mises equivalent stress was examined by moving the lower jig coupled with the bolt 0.1 mm downward.



(**a**) Boundary condition (**b**) High-strength bolt (**c**) Smart bolt (hole)

Figure 3. Finite element analysis of the smart bolt.

Figure 3a shows the boundary condition of the FEA, Figure 3b is the FEA result of the high-strength M16 bolt without the hole, and Figure 3c is the FEA result of the M16 bolt with the hole. Regardless of the presence or absence of a hole, the maximum equivalent stress of the two models was lower than the yield tensile strength. The location of the maximum equivalent stress and the distribution of the equivalent stress inside the bolt were similar. However, in the case of the bolt with a hole, the equivalent stress was about 30% greater than that without a hole. This is thought to be because of an increase in sensitivity in the analysis due to the presence of a large number of micro-sized grids.

3.2. Smart Bolt Tensile Test and Review of Applicability

The robustness of the smart bolt was confirmed by determining the maximum load through a tensile test of the smart bolt that showed relatively high equivalent stress. Tensile tests were performed on four specimens with a strain gauge inserted. The tensile tests were conducted on two specimens each, at tensile speeds of 1 mm/min and 2 mm/min, as shown in Figure 4.

Figure 4. Results of tensile tests.

The fracture location of the smart bolt occurred close to where the equivalent stress occurred, as confirmed through FEA. The maximum load of each specimen was 170.56 kN on average, as shown in Table 2, and satisfied the 163 kN standard of the 10.9 thread strength class of M16 bolts in ISO 898-1 (minimum ultimate tensile load). This confirmed that there was no loss of robustness due to insertion of the strain gauge into the bolt.

Table 2. Results of tensile tests.

<table>
<tr><th>Specimen No.</th><th>#1</th><th>#2</th><th>#3</th><th>#4</th><th>Avg.</th></tr>
<tr><td>Tensile velocity (mm/min)</td><td>1</td><td>1</td><td>2</td><td>2</td><td rowspan="2">170.56 kN</td></tr>
<tr><td>Max. load (kN)</td><td>177.73</td><td>168.95</td><td>170.15</td><td>165.43</td></tr>
</table>

Although the bolt cross-section was reduced by drilling the inside of the bolt and inserting the strain gauge, it still met the bolt tightening torque required by the standard specification for connections by water supply pipes in Korea (KCS 57 30 20: 2017).

4. Simulated Leak Piping System

4.1. Introduction of Simulated Leak Piping System

To evaluate the leak detection applicability of the smart bolt, a simulated leak piping system was configured, as in Figure 5. The acceleration sensor for detecting leakage signals and the strain sensor for tensile testing used a Radian Co. Ltd. SDL 600R datalogger that can get 1024 Hz sampling data to acquire each measurement raw data. In general, the frequency range of the leak detection equipment using the accelerometer sensor is from 300 Hz to 5000 Hz. Since the smart bolt is in the joint part of the valve, it is expected that damping will occur due to the rubber packing. Therefore, it was set to a lower frequency band than the general frequency range. The simulated leak piping system was composed of a 200-mm main cast iron pipe (total length of 3.2 m) and an 80-mm branch pipe. Both ends of the simulated pipe were put on a jig with free ends. The simulated leak was made to flow through the branch pipe as per normal (height 10 m). The water pressure in supply pipes is generally 0.1~0.5 MPa, and we confirmed that the water pressure in the simulated pipe was 0.18 MPa through a water pressure gauge. For the leak measurement experiments and tensile tests, the smart bolt was installed on the valve joint.

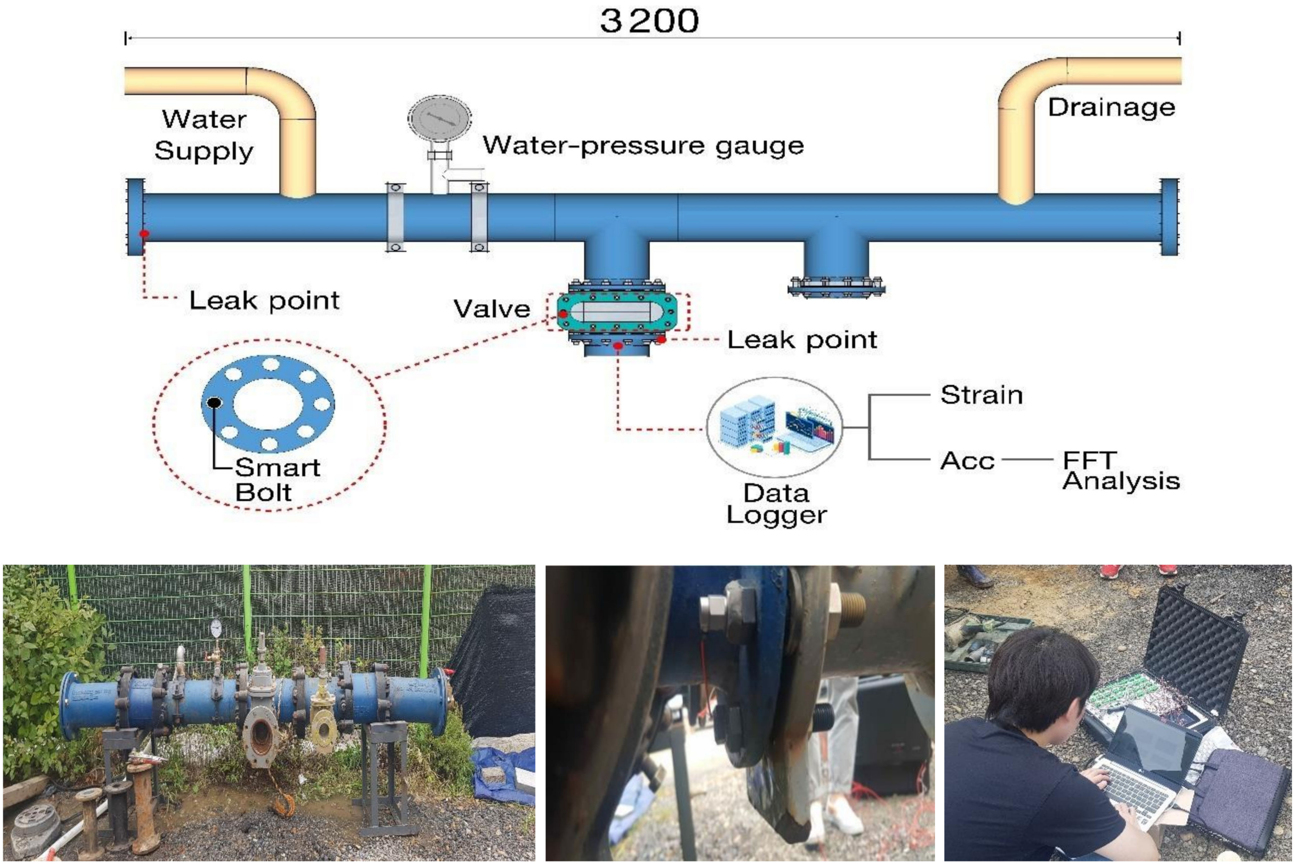


Figure 5. Simulated leak piping system.

4.2. Smart Bolt Strength Tests and Results

The tensile stress was calculated by multiplying the value of the strain caused by the torque of the smart bolt by the modulus of elasticity (205 GPa), as shown in Figure 6. The torque value and the allowable tensile stress of the bolt were compared.

Figure 6. Smart bolt installation and measurement of torque.

Table 3 shows the torque and strength measurement results of the tested smart bolts. There was no visual damage to the bolt when it was 60 N·m, which is the torque value of M16 required by the standard specification for connection by the water supply pipe in

Korea, was applied. The tensile stress calculated from the measured strain was found to be within the allowable tensile stress range of the bolt. With the torque of 70 N·m, the stress of the smart bolts were also calculated to be within the allowable tensile stress range, so it was judged that the smart bolt was suitable for the water supply bolt application.

Table 3. Smart bolt strength tests.

No.	Measurement Torque (N·m)	RMS of Strain (10^{-6})	Tensile Stress (MPa)	M16 Bolt Standard Torque (N·m)	M16 Bolt Allowable Tensile Stress (MPa)
1	10	792	162.3	60	217.32
2	20	800	163.9		
3	30	808	165.6		
4	40	814	166.8		
5	50	821	168.3		
6	60	830	170.2		
7	70	836	171.4		

In addition, the embedded strain gauge was a good sensor for linearity and could determine whether the bolt gets loosened by using the initial (reference) value after the initial bolt installation. As the torque changes, the strain rate of the smart bolt is proportionally changed. Therefore, it may be possible to monitor the bolt loosening by comparing the new measured value and the initial measured value at the corresponding torque.

4.3. Tests of Detecting Leakage Signals

Ten experimental cases were established including no leakage, leakage of the main pipe, leakage of the branch pipe, flow in the pipe, and several cases of different amounts of leakage. The water pressure was 0.18 MPa when there was no flow in the pipe and was 0.17 MPa with the flow in the pipe. Here, as a variable, the leakage signal was measured when there was leakage without a change in the water pressure, and also when there was a change in the water pressure due to a large amount of leakage. Table 4 summarizes the experimental conditions described above.

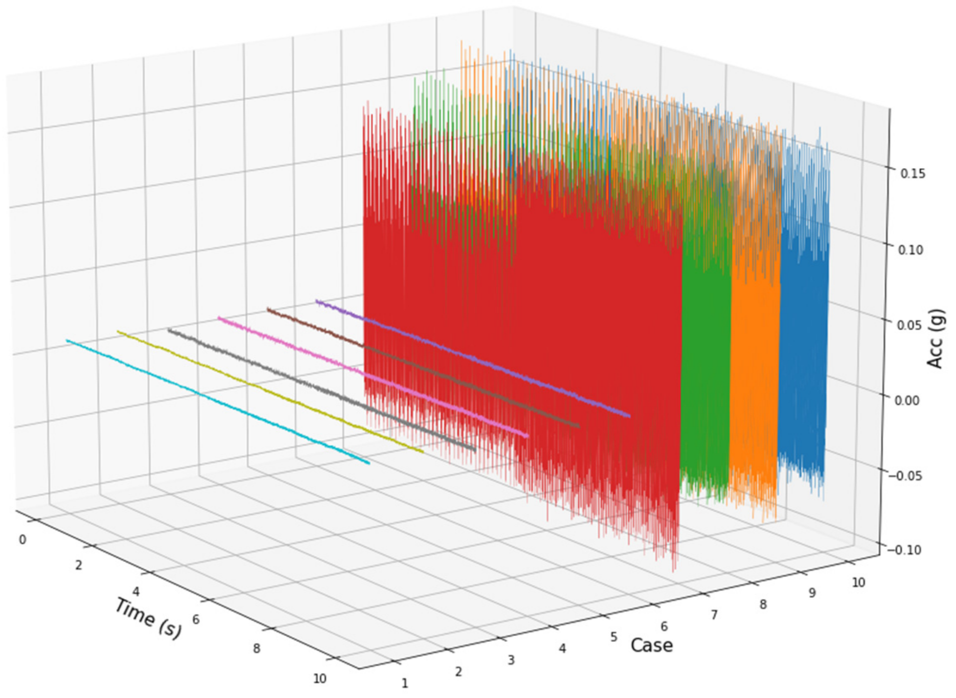
Table 4. Leak testing programs.

Case No.	Leak Point	Water Flow in the Pipe	Water Pressure (MPa)
1	None	No	0.18
2	None	Yes	0.17
3	Valve in branch pipe	No	0.18
4	Valve in branch pipe	No	0.17
5	Valve in branch pipe	Yes	0.17
6	Valve in branch pipe	Yes	0.14
7	Main pipe	No	0.18
8	Main pipe	No	0.14
9	Main pipe	Yes	0.17
10	Main pipe	Yes	0.14

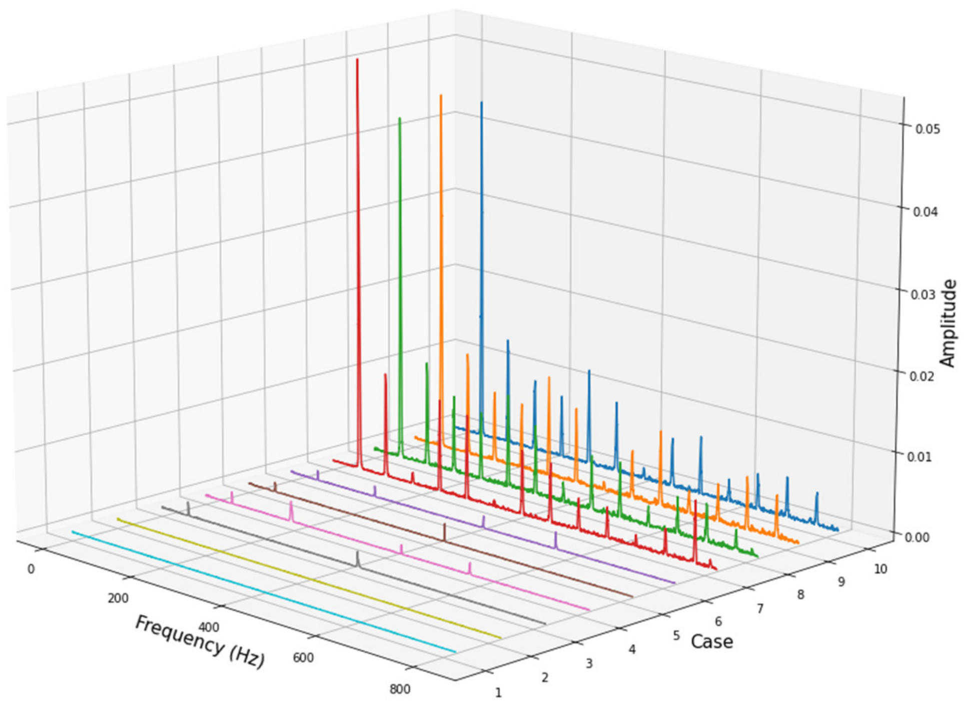
4.4. Results of Leakage Signal Tests

In the coupled vibration mode, the 50–60 Hz band was set as the leak frequency detection band through sample measurement because the leak detection frequency range varies depending on the pipe type; here, the simulated leak piping system was a cast iron pipe [14,23].

Sampling was done at 1024 Hz, and FFT analysis was conducted by setting a low-pass filter (1000 Hz) for data in a low-frequency band. The results of the leakage signal analysis for each case are given in Figure 7b, referring to the case numbers in Table 4.



(**a**) 1000 Hz low pass filter on acceleration (g)



(**b**) fast Fourier transform results

Figure 7. The 1000 Hz low pass filter on acceleration and fast Fourier transform (FFT) results.

Case 1 in Figure 7b is the FFT result of the acceleration in the state where there was no leakage and no flow, and case 2 is where there was flow in the pipe but no leakage (because there was no leakage, there was no signal for the dynamic behavior of the pipe). Cases 3–6 are the cases of leakage from the branch pipe, and cases 7–10 are the cases of leakage from the main pipe. In the case of leakage of the main pipe and the branch pipe, it was divided into the case where the water pressure does not change and the case where the water pressure changes according to the amount of leakage.

When the main pipe leaked rather than the branch pipe, the leak detection signal appeared in the higher-order mode. Conversely, leakage from the branch pipe produced a low-order signal and the leakage signal intervals were wide. In the branch pipe leakage, more leakage signals appeared when there was a large amount of leakage than with a small amount.

5. Discussion

Finite element analysis was performed to confirm the application of the developed smart bolt. Regardless of the presence or absence of holes in the bolt, the maximum equivalent stress used was lower than the yield tensile strength, and the equivalent stress was approximately 30% in the case of the model with holes, compared to the intact model. In the tensile strength test, the average was 170.56 kN, which exceeded the minimum requirement of 163 kN in the 10.9 strength class of M16 bolts. It was possible to determine whether the bolt was loosened using the initial (reference) value and the measured value at the specified torque that determined the bolting action.

Generally, when the ring frequency is related to the coupled vibration in 65 A, PVC (Poly Vinyl Chloride) has 7559 Hz, steel pipe has 23,111 Hz, and the cast-iron pipe has 23,801 Hz [12,14]. Figure 8 shows the audible range of the leak detection equipment and the frequency range of the leak sound.

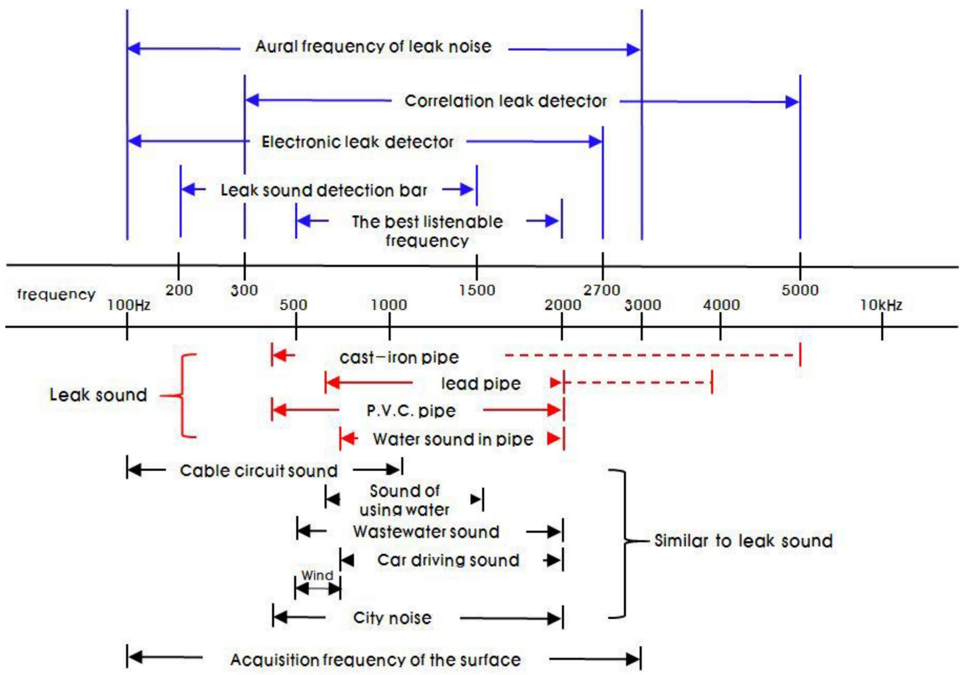


Figure 8. Audible range of leak detection equipment and frequency range of leak noise.

The leakage sound frequency range was between about 500 Hz and 2000 Hz, and the frequency range in cast iron pipes was about 400 Hz to 5000 Hz. An acoustic emission sensor is used for a relatively short range, and it is difficult to process noise similar to leakage sound [12,16]. For long-distance detection, it is common to measure the vibration of a pipe that causes a coupled vibration using an acceleration [16].

When fluid and piping are coupled, the leakage vibration appears at low frequency, unlike sound wave transmission directly connected to leak detection [24]. Although it is a cast iron pipe that has a relatively high-frequency band, it was set to a lower frequency band because of the pipe with free ends and the rubber packing of the joint.

The results of the leak detection test with the acceleration sensor are as follows. FFT analyses of cases 1 and 2 detected no leakage signal regardless of whether there was flow in the pipe. When there was leakage from the branch pipe valve (cases 3–6), it was confirmed that the leakage signal of the first mode in the 60-Hz band was detected. When there was a large amount of leakage, even the fourth-mode signal was detected; in leakage from the main pipe (cases 7–10), it was confirmed that the leak signal was continuously detected at 60-Hz intervals after the first detection, and the same result was obtained regardless of the amount of leakage in the main pipe. The frequency response of the main pipe leakage was about 100 times greater than that of the branch pipe.

When the main pipe leak occurred, the leak signal was larger than that of the branch pipe valve, and even higher-order mode responses were detected at regular intervals. The cause seemed to be a leakage in the valve joint and rubber packing: As the joint of the valve and the rubber packing directly act as damping, it seemed that the leakage signal measurement was clearly measured at low frequencies where the effect of damping was small, rather than at high frequencies where the effect of damping was large. In addition, when the main pipe leaked, we believe that the leak signal in the relatively high-frequency band was measured because the whole pipe was subjected to coupled vibration.

Through these fundamental experiments, we confirmed the ability of the smart bolt to detect leak signals of the water supply valve. However, more verification through various future field experiments is needed such as with various pipe types and ground boundary conditions. Furthermore, additional development of the transmit/receive module and the power supply for the smart bolt is required for effective monitoring.

6. Conclusions

This study involved basic experimental assessments of the ability of modified smart bolts to detect water pipe valve leakage and the loosening of bolts, which are among the main causes of leakage in municipal water supply networks.

The developed smart bolt had a strain gauge inserted in a customized hole and an acceleration sensor attached to the top of the bolt. Through FEA and tensile strength tests, the strength of the bolt met the standard specification for water supply pipe connections in Korea (KCS 57 30 20: 2017) and also met the ISO 898-1 requirement to perform within the allowable tensile strength range of such bolts. Therefore, the smart bolt can be safely applied to the water supply valve fastening mechanism, and we determined that it is possible to monitor the loosening state of the bolt by setting the threshold value of the strain gauge according to the torque.

In addition, we analyzed the frequency response of the simulated leakage pipe system depending on the leakage of the valve and the main pipe in 10 scenarios. An acceleration sensor installed in the smart bolt detected a leak signal in the 60-Hz band when the valve leaked. When the main pipe leaked, a higher-order mode frequency response occurred than when the valve leaked, probably due to the characteristics of the cast iron pipe, the rubber packing (which plays a direct damping role), and the simulated leakage pipe system being in an unconstrained state.

This paper presents a basic experiment to detect water leakage and monitor bolt loosening by applying the developed smart bolt, and the applicability of the smart bolt in water supply valve was confirmed. Development for the system construction such as the power modules, wireless communication modules, monitoring programs, and leak detection algorithms is in progress. In the future, comparative experiments with various sensors and field application experiments of a real water distribution system would be required.

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