International Journal of Control and Automation
Vol.8, No.11 (2015), pp.349-360
http://dx.doi.org/10.14257/ijca.2015.8.11.33

A Scheme of Impulse Noise Mitigation for Vibration Measurement Using Wireless Accelerometers

Surgwon Sohn, In Jung Lee and Seong-Rak Rim

Div. of Computer and Information Eng., Hoseo University
sohn@hoseo.edu

Abstract

Low-cost wireless sensor nodes have become more important in the area of modern structural health monitoring (SHM) the power consumption and cost of the wireless sensor nodes play an important role in the development of modern SHM. This paper presents a low-cost wireless vibration measurement method using wireless sensor nodes. To improve the quality of the signals from the wireless accelerometer, an alpha-trimmed filter is considered to mitigate impulse noise. In order to demonstrate their feasibility to the SHM, experimental modal analysis for a cantilever beam has been carried out and compared with the conventional wired vibration measurement system. Experimental results show the feasibility of using low-resource wireless sensor nodes for structural health monitoring.

Keywords: *Vibration Measurement, Experimental Modal Analysis, Alpha-trimmed Filter, Structural Health Monitoring*

1. Introduction

Structural health monitoring (SHM) is crucial for protecting structures against wind, aging, and potential collapse. Since wireless sensor nodes reduce the time and cost of installation and maintenance for the SHM, the use of wireless sensor networks (WSNs) has recently become an area of interest [1]. Modern, wireless-based SHM has two main constraints: cost and power consumption. Micro electro-mechanical system (MEMS) accelerometers meet these conditions. A wireless sensor node is also important since it deals with vibration data acquisition and wireless transmission. Many researchers choose commercial off-the-shelf products as their wireless sensor nodes rather than building their own prototypes because of their performance and ease of implementation. For such a reason, we also choose a commercial low-cost wireless sensor node that is composed of a MEMS accelerometer, Arduino compatible processor board, and IEEE 802.15.4 communication module.

To better understand any structural dynamic problems, the resonant frequencies of a structure need to be identified and quantified. Today, experimental modal analysis has become a widespread means of finding the modes of vibration of a structure. Modal analysis is the field of measuring and analyzing the dynamic response of structures during excitation [2]. The frequency response function (FRF) describes the input-output relationship between two points on a structure as a function of frequency [3]. Experimental modal parameters, such as natural frequency, damping ratio, and mode shape, are also obtained from a set of FRF measurements.

This paper presents an experimental modal analysis of a cantilevered steel beam using a low-cost wireless sensor node for SHM in order to demonstrate the feasibility of its use. For the purpose of this end, we apply an alpha-trimmed filter to the raw vibration signals acquired by a wireless accelerometer. Dynamic characteristics of the structures, such as natural frequencies, damping ratios, and mode shapes are acquired. These dynamic properties are here compared with the

ISSN: 2005-4297 IJCA

results of a conventional wired vibration measurement system. In this paper, mathematical modeling of a cantilever beam is described in Section 2. Section 3 depicts the vibration signal enhancement using an alpha-trimmed filter for impulse noise mitigation. The experimental modal analysis using the selected wireless accelerometer is briefly described and the test results are compared in Section 4.

2. Mathematical Model of Single Degree-of-Freedom System

A mathematical model can be used to represent the characteristics of the system. The simplest model is the single degree-of-freedom (SDOF) mass, spring, dashpot model which is shown in Figure 1. The aim of developing the SDOF mathematical model is to use it in order to find the position $x(t)$ of the moving mass m at any instant of time, also often velocity $\dot{x}(t)$ and acceleration $\ddot{x}(t)$. The SDOF vibration can be analyzed by Newton's second law of motion, $F = ma$. The resulting equation of motion is a second order, non-homogeneous, ordinary differential equation.

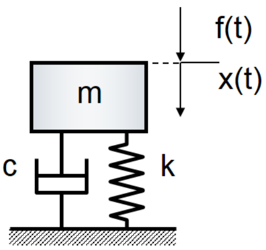


Figure 1. Schematic of a Single-Degree-of-Freedom System

Using a simple force balance on the mass of Figure 1 in the x direction, the equation of motion for $x(t)$ becomes

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{1}$$

where m is the mass, c is the damping and k is the stiffness with the displacement, velocity and acceleration and the forcing function.

A system is said to be a cantilever beam system if one end of the system is rigidly fixed to a support and the other end is free to move. For a cantilever beam subjected to free vibration, and the system is considered as continuous system in which the beam mass is considered as distributed along with the stiffness of the shaft, the equation of motion can be written in [4] as follows.

$$\frac{d^2}{dx^2}\left\{EI(x)\frac{d^2Y(x)}{dx^2}\right\} = \omega_n^2 m(x)Y(x) \tag{2}$$

where, E is the modulus of rigidity of beam material, I is the moment of inertia of the beam cross-section, $Y(x)$ is displacement in y direction at distance x from fixed end, ω_n is the circular natural frequency, m is the mass per unit length, $m = \rho A(x)$, ρ is the material density, $A(x)$ is the area of cross-section of the beam, x is the distance measured from the fixed end. Following are the boundary conditions for a cantilever beam [5].

$$at \quad x = 0, \; Y(x) = 0, \; \frac{dY(x)}{dx} = 0 \tag{3}$$

$$at \quad x = l, \quad \frac{d^2Y(x)}{dx^2} = 0, \quad \frac{d^3Y(x)}{dx^3} = 0 \tag{4}$$

For a uniform beam under free vibration from Equation (2), we get

$$\frac{d^4Y(x)}{dx^4} - \beta^4 Y(x) = 0 \text{ where } \beta^4 = \frac{\omega_n^2 m}{EI} \tag{5}$$

Using the boundary condition from Equation (3) and (4), we obtain the frequency equation as

$$\cos\beta_n L \cosh\beta_n L = -1 \tag{6}$$

where L is the length of the beam. The Equation (6) must be solved numerically and it yields an infinite of solutions of β_n. The relative displacement configuration of the vibrating system for a particular natural frequency is known as the eigen function in continuous system. Corresponding to the eigen values of β_n, the mode shapes for a continuous cantilever beam is given in [6]

$$\begin{aligned} f_n(x) = A_n\{&(\sin\beta_n L - \sinh\beta_n L)(\sin\beta_n x - \sinh\beta_n x) + \\ &(\cos\beta_n L - \cosh\beta_n L)(\cos\beta_n x - \cosh\beta_n x)\} \end{aligned} \tag{7}$$

where $n = 1,2,3,\ldots,\infty \quad and \quad \beta_n L = \alpha_n$

A closed form solution of the circular natural frequency ω_n, from above equation of motion and boundary conditions, can be written as

$$\omega_n = \alpha_n^2 \sqrt{\frac{EI}{mL^4}} \tag{8}$$

The Equation (8) is satisfied by a number of values of $\beta_n L$ corresponding to each normal mode of oscillation, which for first three modes are given as:

$\alpha_n = 1.875, \quad 4.694, \quad 7.855$

Thus, first three mode shapes $(f_1(x), \ f_2(x), \ f_3(x))$ and natural frequencies $(\omega_1, \ \omega_2, \ \omega_3)$ are shown in Figure 2.

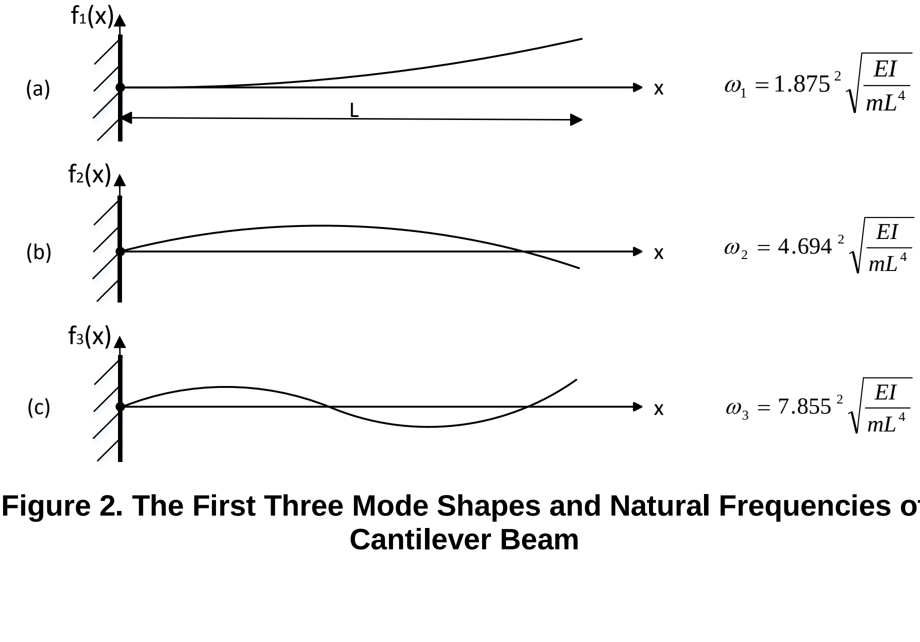


Figure 2. The First Three Mode Shapes and Natural Frequencies of Cantilever Beam

where I, the moment of inertia of the beam cross-section [7]

$$I = \frac{bd^3}{12} \tag{9}$$

where b and d are the breadth and width of the beam cross-section [6].

The cantilever steel beam studied in this paper is long, thin, cantilever beam. One end of the beam is fixed, while the other end is free. The origin of the coordinate axis is at the fixed end. A typical beam, used in this study, is L = 900 mm long, b = 60 mm wide, and d = 3 mm thick. The mass per unit length $m = \rho A$, where ρ is $7{,}850\, kg/m^3$ for material density, E is $2.1 \times 10^{11}\, N/m^2$ for Young's Modulus. From the Equation (8), we get the first circular natural frequency

$$\omega_1 = 1.875^2 \sqrt{\frac{E\left(bd^3/12\right)}{\rho b d L^4}} = 1.875^2 \sqrt{\frac{Ed^2}{12 \rho L^4}} = 1.875^2 \sqrt{\frac{2.1 \times 10^{11} \times 0.003^2}{12 \times 7850 \times 0.9^4}} = 19.44 \text{ rad/sec}$$

So, $f_1 = \omega_1 / 2\pi = 3.09 Hz$

The above natural frequency has to be modified since there is a mass in the form of an accelerometer at the free end of the continuous beam. By continuous approach the solution is difficult since with tip mass the boundary condition at free end is now time dependent. Let us consider the beam specimen as mass-less with stiffness k and has a discrete effective mass, m_{eff}, at the free end, which produces the same frequency as a continuous beam specimen without any tip mass. Hence, the natural frequency of discrete model of the beam without an accelerometer can be written as

$$\omega_1 = \sqrt{\frac{k}{m_{eff}}} \quad \text{with} \qquad k = \frac{3EI}{L^3} \tag{10}$$

From which the effective mass at the tip can be written as

$$m_{eff} = \frac{3EI}{L^3 \omega_1^2} \quad \text{with} \qquad \omega_1 = 1.875^2 \sqrt{\frac{EI}{mL^4}} \tag{11}$$

where m is the mass per unit length, so $m = \rho A$, but the real mass of the beam, $m_b = \rho A L = 7850 \times 0.06 \times 0.003 \times 0.9 = 1.2717 Kg$, so m_{eff} becomes

$$m_{eff} = \frac{3EI}{L^3} \frac{mL^4}{1.875^4 EI} = \frac{3mL}{1.875^4} = 0.243 m_b = 0.309 Kg$$

Now, if we consider the mass of accelerometer, m_{acc}, at the free end of the beam, then the total mass at free end will be

$$M = m_{eff} + m_{acc}$$

So for the discrete beam with accelerometer, the theoretical first natural frequency after considering the mass of accelerometer will be

$$\omega_1 = \sqrt{\frac{k}{M}} \tag{12}$$

Now, let us consider that two accelerometers are used. The mass of the first wire-based accelerometer would be 51 gram, and in this case, coaxial cable must be considered, too. From the Equation (12), we get the first circular natural frequency as follows.

$$\omega_{1\_acc1} = \sqrt{\frac{3\times 2.1\times 10^{11}\times 1.35\times 10^{-10}}{(0.309+0.051)\times 0.9^3}} = 18.00 \text{ rad/sec}$$

So, $f_{1\_acc1} = \omega_{1\_acc1} / 2\pi = 2.87Hz$. If we consider the weight of coaxial cable, then the frequency would be lower than this value.
In the second case, the type of accelerometer is wireless accelerometer, so it is not necessary to consider the cable weight, but we have to consider the battery weight instead. The total weight would be 175 gram. Then

$$\omega_{1\_acc2} = \sqrt{\frac{3\times 2.1\times 10^{11}\times 1.35\times 10^{-10}}{(0.309+0.175)\times 0.9^3}} = 15.53 \text{ rad/sec}$$

So, $f_{1\_acc2} = \omega_{1\_acc2} / 2\pi = 2.47Hz$.

In our case, we use PCB 603C01 ICP type accelerometer which has a weight of 51gram. In other case, we use also LIS331DLH MEMS type accelerometer embedded into a Waspmote sensor node which has a weight of 20gram. In addition to the Waspmote, Lithium ion battery of 6600mA with 155gram is attached to the Waspmote, so total weight of wireless accelerometer becomes 175gram.

3. Impulse Noise Mitigation Using Alpha-trimmed Filter

The raw signals acquired from the wireless accelerometer have impulse noise because the input signal to the cantilever beam is obtained from the impact hammer and wireless accelerometer does not provide any good filters for removing impulse noise. To mitigate the impulse noise in time domain, we propose a method that operates directly on the signals. Time domain processing will be denoted by Equation (13).

$$g(t) = T\{x(t)\} \tag{13}$$

where *x(t)* is the input signal, *g(t)* is the processed signal, and *T* is an operator on *x(t)*, defined over some neighborhood of *x(t)*. *T* can operate on a set of input signals, such as performing the neighborhood signals for noise reduction. The Median filters are popular because, for certain types of random noise, they provide excellent noise-reduction capabilities. The median filter's operation is given by Equation (14) where *S* is a set of surrounding neighborhood at one time.

$$g(t) = \underset{t\in S}{median}\{x(t)\} \tag{14}$$

In order to perform median filtering at a point of signal, the median is calculated by first sorting all the values from the surrounding neighborhood into numerical order and then replacing the signal being considered with the middle value. The alpha trimmed filter, which is windowed filter of nonlinear class by its nature, is hybrid of the mean and median filters. The basic idea is to order elements of the signal discarded at the beginning and at the end of the ordered set and then calculate average value using the rest. A filter formed by averaging these remaining signals is called an alpha trimmed mean filter, and represented by Equation (15).

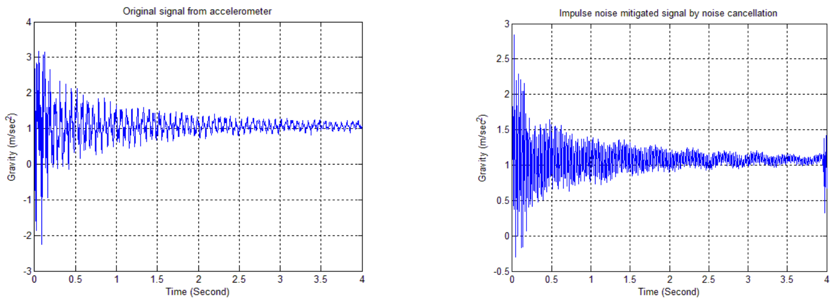
$$g(t) = \frac{1}{n-d}\sum_{t\in S} x(t) \tag{15}$$

where the value of *d* can range from *0* to *n-1*. When *d=0*, the alpha-trimmed filter reduces to the arithmetic mean. If *d =(n-1)/2*, the filter becomes a median filter.

A simplest model of vibration is the SDOF mass-spring-dashpot model defined by second order differential equation with constant coefficients as represented by Equation (1). If we assume that the output signal *x(t)* is measured from the accelerometer. In this case, the output signal *x(t)* has impulse noise. When the above alpha-trimmed filter is applied to the signal, the impulse noise is mitigated. In the equation (1), let $f(t)=\delta(t)$, then $x(t)=h(t)$ and

$$x(t)=e^{\frac{-a}{2}}\cos\left(\frac{d}{2}t-\frac{4\pi}{d}\right) \tag{16}$$

where $\delta(t)$ is a Dirac-delta function, $h(t)$ is inverse Fourier transform of frequency response function (FRF) and $a=\frac{c}{m}$, when $d=\sqrt{-(a^2-4b)}, b=\frac{k}{m}$. An original signal and filtered signal are shown in Figure 3.



(a) Original Signal (B) Impulse Noise Mitigated Signal

Figure 3. The Original and Impulse Noise Mitigated Signal from Accelerometer

4. Performance Evaluation Using Experimental Modal Analysis

4.1. Wireless Sensor Node

Functional subsystems of WSN are sensing interface, computational core, and actuation interface as shown in the previous research [8]. By keeping in mind the low-resources, we have selected a commercial off-the-shelf product, Libelium Waspmote [9], that includes ATmega 1281 micro-controller. It has 8 kb SRAM, 4 kb EEPROM, 128 kb flash memory, and 2 gb SD memory. For saving the power consumption, there are 4 modes; On: 15mA, Sleep: 55 μA, Deep sleep: 55 μA, Hibernate: 0.7 μA. It automatically selects the appropriate power supply (USB or external power), eliminating the need for the power selection jumper. It also has 7 Analog (I), 8 Digital (I/O), 1 PWM, 2 UART, 2 I2C, 1 USB, and 1 SPI for I/O.

A low cost accelerometer sensor, LIS331DLH, is built into the Waspmote that is used to measure the accelerations of the cantilever beam. It has three scales (±2g, ±4g, ±8g) and seven work modes which is important in case of battery operated products. In normal mode, the output data rate can be 50 Hz / 100 Hz / 400 Hz / 1000 Hz. But in low power mode, it can be 0.5 Hz / 1 Hz / 2 Hz / 5 Hz / 10 Hz. A ZigBee-802.15.4-Pro 802.15.4 rf module is used for a wireless data transmission to satisfy the low resources. It operates -100 dB sensitivity within the ISM 2.4 GHz frequency band. It has 100 mW EIRP power output (up to 7000 m outdoor range), RPSMA connector. To interface this rf module on the Waspmote, it needs a Waspmote gateway. It communicates with the host PC via IEEE 802.15.4/ZigBee protocol. Figure 4 shows the Waspmote with the ZigBee module and Waspmote gateway.

Figure 4. Waspmote with Zigbee and the Host Gateway

To investigate a suitability of low-resource wireless sensor node in a SHM, an experimental modal analysis for a cantilevered steel beam is carried out [10]. The frequency response function was performed at the host PC using Smart Office Analyzer software [11] with the 1,024 sample of data.

4.2. Experimental Setup

To study the accuracy of the dynamic acceleration measurement obtained with a wireless accelerometer such as LIS331DLH on the Waspmote, we used a conventional wired IEPE accelerometer to measure the transient response of a cantilever beam simultaneously. The experimental modal analysis of a simple cantilever beam was performed to demonstrate the use of wireless sensor nodes.

A cantilevered steel beam was used for the experiment with approximate dimensions of 900 x 60 x 3 mm. An IEPE or ICP type impact hammer, model 086C03 of PCB Piezotronics, was used as the excitation source at any point input and response data was acquired at the point of the beam. A cable with the hammer is connected to the NI-9234 as data acquisition hardware. A wired accelerometer, 603C01 of PCB Piezotronics, was used for the reference. A MEMS accelerometer, LIS331DLH built on the Waspmote, is located at the end of the cantilever beam and the excitation was imparted on the point as shown in Figure 5.

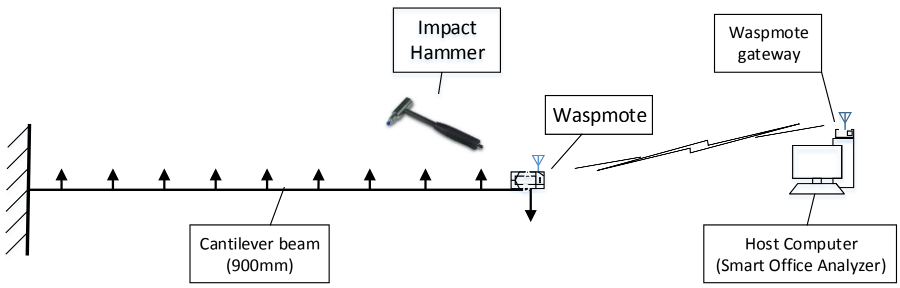


Figure 5. Test Setup and the Data Acquisition Point

In this test, we use a fixed accelerometer and a roving hammer as excitation and give a multiple-input, single-output (MISO) analysis. We have chosen 10 excitation points as an input force to obtain 3 mode shapes. A frequency response function is acquired by computation of the cross power spectrum of the input and output vibration data using commercial Smart Office Analyzer software. The measurement for experimental modal analysis is to acquire frequency response function data from a test structure. As the cantilever beam setup was excited with the hammer manually the response of the structure was measured in the form of acceleration. Both the excitation and response signal were sent to the data acquisition hardware with a signal processing software. Figure 6 depicts an IEPE type wired accelerometer with the cantilever beam while Figure 6 shows the Waspmote, which is composed of accelerometer, processor, communication device, and a battery on a cantilever beam for experimental modal test. The Waspmote communicates with the host PC using a gateway device via the IEEE 802.15.4 protocol.

Figure 6. A Wired Accelerometer on a Cantilever Beam

Figure 7. A Wireless Accelerometer on a Cantilever Beam

Sampling rate of the wired ICP accelerometer was 256 Hz, and the vibration signal was collected for 4 seconds, so a total of 1,024 samples were recorded for post-processing. In case of wireless accelerometer, the sampling rate of the LIS331DLH was 400 Hz, but the vibration data was recorded at a rate of 256 Hz for 4 seconds.

4.3. Test Results

The signal processing software, Smart Office Analyzer, was used to capture and analyze the signal acquired from the both ICP accelerometer and LIS331DLH on the Waspmote. The modal frequencies were estimated as the frequencies where we received maximum gain in the frequency response function plots in Smart Office Analyzer. Figure 8 and Figure 9 represent frequency response function of the wired and wireless accelerometer respectively.

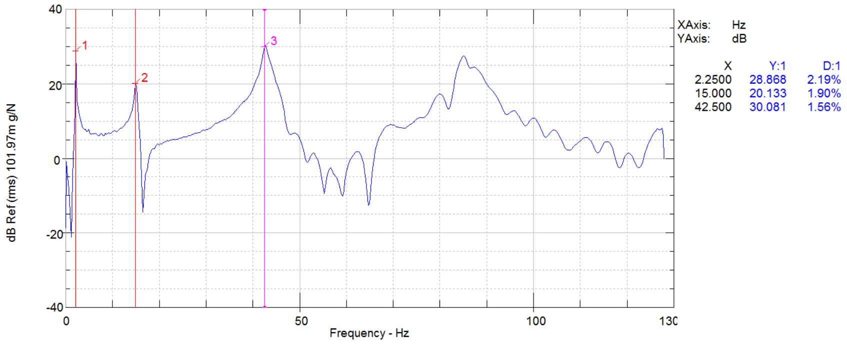


Figure 8. Frequency Response Function Using Wired IEPE Accelerometer

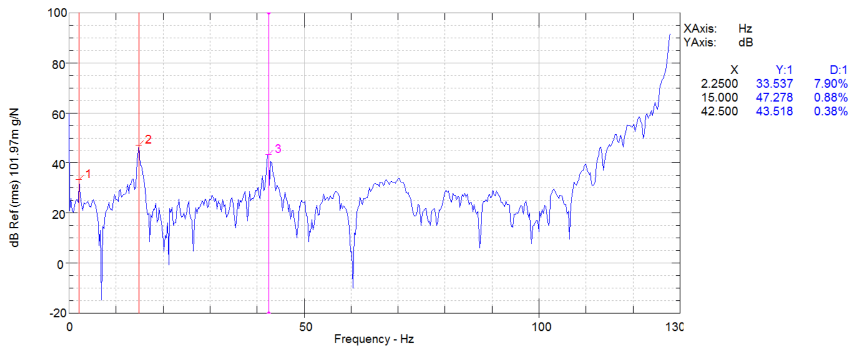


Figure 9. Frequency Response Function Using Wireless MEMS Accelerometer

The Figure 10 illustrates the frequency response function of the wireless accelerometer after applying alpha-trimmed filter as a method of impulse noise mitigation. However, the dynamic properties, such as natural frequencies, are the same as before applying the filter. The natural frequencies which were acquired from the analytical modeling and the experiments are compared in the Table 1.

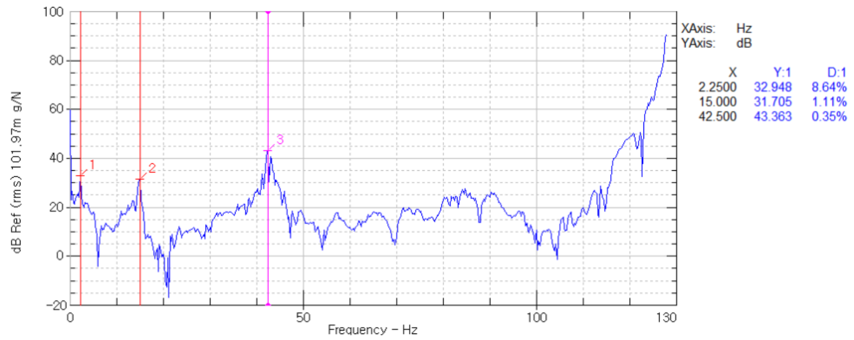


Figure 10. Frequency Response Function Using Alpha-Trimmed Filter for Wireless MEMS Accelerometer

Table 1. Modal Frequencies and Damping Ratios

Mode		Analytical Modeling (wireless type)	wired ICP type	wireless MEMS type	Alpha trimmed filtered
1st	modal frequency (Hz)	2.47	2.25	2.25	2.25
	damping ratio (%)	n/a	2.19	7.9	8.64
2nd	modal frequency (Hz)		15	15	15
	damping ratio (%)	n/a	1.9	0.88	1.11
3rd	modal frequency (Hz)		42.5	42.5	42.5
	damping ratio (%)	n/a	1.56	0.38	0.35

5. Conclusion and Future Works

In this paper, the feasibility of using wireless sensor nodes on a vibration measurement was investigated. To improve the performance of wireless accelerometers, the alpha-trimmed filter was applied to the raw vibration signals to mitigate the impulse noise. In order to justify the performance of wireless accelerometers, the experimental modal analysis for the cantilever beam was carried out. To verify the feasibility of its use, the dynamic properties of the structures such as natural frequencies, damping ratios, and mode shapes of the cantilever beam are obtained and compared with the conventional wired IEPE vibration measurement system. These properties were computed by Smart Office Analyzer software. A further step of the research is to design wireless sensor networks of the SHM applications. Expecting issues would be data transmission bandwidth and time synchronization [12].

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2014-0024242).

References

[1] M. Bocca, L.M. Eriksson, A. Mahmood and R. Jantti, "A Synchronized Wireless Sensor Network for Experimental Modal Analysis in Structural Health Monitoring", Computer-Aided Civil and Infrastructure Engineering. 26, 483-499 **(2011)**.
[2] B.J. Schwarz and M.H. Richardson, "Experimental Modal Analysis. CSI Reliability Week", **(1999)** FL USA.
[3] H.A. Al-Khazali and M. Askari, "Calculations of Frequency Response Functions Using Computer Smart Office Software and Nyquist Plot under Gyroscopic Effect Rotation", Int'l J. of Computer Science and Information Technology & Security . 1, 2 **(2011).**
[4] L. Meirovitch, "Analytical methods in vibrations", Macmillan, Michigan, USA **(1967).**
[5] "Free Vibration of a Cantilever Beam (Continuous System)", http://iitg.vlab.co.in/index.php?sub=62&brch=175&sim=1080&cnt=1.
[6] J. Humar, "Dynamics of Structures: second edition", Taylor & Francis, London, U.K. **(2002).**
[7] J. Giordano and Y. Burtschell, "Confrontation of genetic Algorithm Optimization process with a New reference Case: Analytical Study with Experimental Validation of the Deflection of a Cantilever Beam", Int'l J. of Advanced Science and technology. 49, 105-118, **(2012).**
[8] P.D. Chougule, P.H. Kirkegaard and S.R.K. Nielsen, "Low Cost Wireless Sensor Network for Structural Health Monitoring", In Scandinavian Vibration Forum (SVIB) **(2010).**
[9] "Waspmote Datasheet", http://www.libelium.com/products/waspmote.
[10] S. Sohn, S.R. Rim and I.J. Lee, "Vibration measurement of Wireless Sensor Nodes for Structural Health Monitoring", Advanced Science and Technology Letters, 98 (CES-CUBE 2015), 18-22, **(2015).**
[11] "Smart Office Analyzer", https://www.mpihome.com/en/products-solutions/dynamic-signal-analysis.html.
[12] Y. Lim and J. Park, "networking Strategies for Structural Health Monitoring in Wireless Sensor Networks", Int'l Journal of Energy, Information and Communication. 6, 3, 11-18, **(2015).**

Authors

Surgwon Sohn, He is a professor in the division of computer and information engineering at the Hoseo University. His current research interests include wireless sensor networks, mobile computing, radio resource management, and constraint optimization. Professor Sohn received the B.S., M.S. and Ph.D. degrees all from Inha University, Korea.

In Jung Lee, He is a professor in the division of game engineering at Hoseo University where he has been since 1992. Before joining Hoseo University, He was an lecturer in KAIST for one and half year 1991-1992. His current research interests include image processing and discrete mathematics. Professor Lee received and M.S. and PhD. in Mathematics from ChungAng University, Korea, and PhD. in Engineering of Electronics from Ajou University.

Seong-Rak Rim, (srrim@hoseo.edu) he has been a professor in the division of computer and information engineering at the Hoseo University since 1993. His current research interests in Embedded Systems, especially Smart Sensor Nodes for SHM. He received B.S. from Sogang University, M.S. and Ph.D. in Computer Engineering from Seoul National University, Korea.