On-Line Structural Damage Localization and Quantification Using Wireless Sensors

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Abstract

In this paper, a wireless sensing system is designed to realize on-line damage localization and quantification of a structure using a frequency response function change method (FRFCM). Data interrogation algorithms are embedded in the computational core of the wireless sensing units to extract necessary structural features, i.e. the frequency spectrum segments around eigenfrequencies, automatically from measured structural response for the FRFCM. Instead of the raw time-history of the structural response, the extracted compact structural features are transmitted to the host computer. As a result, with less data transmitted from the wireless sensors, the energy consumed by the wireless transmission is reduced. To validate the performance of the proposed wireless sensing system, a 6-story steel building with replaceable bracings in each story is instrumented with the wireless sensors for on-line damage detection during shaking table tests. The accuracy of the damage detection results using the wireless sensing system is verified through comparison to the results calculated from data recorded of a traditional wired monitoring system. The results demonstrate that by taking advantage of collocated computing resources in wireless sensors, the proposed wireless sensing system can locate and quantify damage with acceptable accuracy and moderate energy efficiency.

07.05.Hd Data acquisition: hardware and software

07.05.Kf Data analysis: algorithms and implementation; data management

89.20.Kk Engineering

Keywords: wireless sensors, structural health monitoring, damage detection, damage assessment, frequency response function

1. Introduction

Since the mid-1990s, a number of research teams in both academia and industry have proposed an impressive array of wireless sensing unit prototypes to be implemented for structural health monitoring [1]. The essential part of a wireless sensing systems (WSS) is the wireless sensing unit (WSU) which generally consists of three or four functional subsystems: sensing interface, computational core, wireless transceiver and, for some, an actuation interface. A benefit of wireless structural monitoring systems is that they are inexpensive to install because extensive wiring is no longer required between sensors and a central data acquisition system. Furthermore, wireless sensing network is not simply a substitute for traditional tethered monitoring systems but also a decentralized architecture offering parallel processing of measured data. The collocated computational power endows wireless sensing systems great potential for research community to discover.

Researchers have utilized the decentralized parallel computing resources in a WSS by employing local data processing algorithms in the WSU for structural health monitoring purpose. By reducing the size of data to be transmitted, data communication, which is the most significant source of power consumption of the wireless sensing units, can be reduced. Therefore, minimizing the need to transfer time-histories of structural response data by programming wireless sensing units to locally interrogate their data first seems to be one of the appropriate solutions to improve the overall energy efficiency of the wireless structural monitoring system.

Since the end of 1990s, researchers were trying to embed modal analysis and damage detection algorithms into wireless sensing units for damage detection purpose. Straser and Kiremidijan [2] were the first to embed civil structural health monitoring algorithms in WSUs. The normalized Arias intensity which is essentially determined by summing the square of the structural acceleration measured over an earthquake event is calculated within WSUs as a damage indicator for damage assessment. Damage existence and locations of a structure can be assessed by the difference of the energy profile between different floors of a building immediately following an earthquake. Tanner et al. [3] apply a statistical process control (SPC) algorithm to detect the existence of damage of a small bolted frame structure. Two accelerometers mounted across each joint of the structure are connected to a WSU. Preload of the bolt is released by varying the input voltage to a piezoelectric actuator underneath the head of the bolt. The cross-correlation coefficients between the two measured acceleration time-histories under the vibration generated by an electromagnetic shaker are processed locally on a WSU. An alarm will be triggered automatically if an outlier is indicated. Caffrey et al. [4] propose to detect damage of a structure by assessing change in modal frequencies and signal energy contained in each corresponding mode. Fourier spectra of structural acceleration time-histories are calculated in each WSU. After the modal frequencies and modal signal energy contributions are determined in the WSUs, they are transmitted to the host computer to perform damage assessment. The proposed approach is verified by detecting the presence of damage of the IASC-ASCE Structural Health Monitoring Benchmark Structure. Lynch et al. [5] apply a two-tiered time-series damage detection algorithm, the autoregressive (AR) and autoregressive model with exogenous inputs (ARX) prediction model, to automatically detect damage of a lumped-mass laboratory structure using a WSS. The coefficients of an AR model is calculated in the WSUs and transmitted to the host computer. The residual error of the ARX model of the measured data computed in the WSUs is used to determine the presence of damage in the structure. The same damage detection algorithm is later successfully applied to detect damage of nearly full-scale single-story reinforcement-concrete frames [6]. Gao et al. [7] propose a distributed computing strategy using WSUs which apply a flexibility-based damage detection method to assess local health condition of a truss-structure. Adjacent WSUs are grouped together as a community via a hierarchical strategy. After the WSUs in each group transmit raw time-history data to a group-head WSU, the flexibility matrix are constructed using modal parameters identified by Natural Excitation Technique (NExT) and Eigenvalue Realization Algorithm (ERA). Damage Locating Vectors (DLV) are then computed in each community to detect damage. Nagayama et al. [8] later improve this strategy by introducing stochastic DLV which eliminates the need to estimate normalization constants. The improved method is verified through applying to a laboratory 3D truss structure. Hackmann et al. [9] try to localize damage of a structure based on Damage Location Assurance Criterion (DLAC) method. The DLAC method locates damage by comparing the identified modal frequencies of each WSU to a frequency database generated by simulation of different damage patterns of an analytical model of the structure. The wireless sensors perform fast Fourier transform (FFT), power spectrum analysis (PPA) and fractional polynomial curve fitting (FPCF) to determine measured frequencies. The proposed approach is verified by both a cantilever beam and a 3D truss structure with single damage location. Hackmann et al. [10] later propose another approach which uses the Angles-between-String-and-Horizon Flexibility-based Method (ASHFM) and the Axial Strain Flexibility-based Method (ASFM) to detect damage of a beam structure and an analytical truss structure, respectively. After the modal frequencies are selected in WSUs using similar algorithms of the previous paper, the spectrum data of the selected modal frequencies are transmitted to other WSUs. The cross spectral density (CSD) matrices are calculated and singular value decomposition (SVD) is performed on the CSD matrices at each modal frequency to obtain mode shapes. Finally the modal frequencies and mode shapes are transmitted to the host computer to assess damage. Wang et al. [11] apply transmissibility functions analysis to detect damage locations of a 2D steel portal frame using mobile WSUs. The Fourier spectrum of measured acceleration time-history is calculated in each WSU. The FFT results within the interested frequency range are transmitted to other WSUs. The damage indicators are determined by the transmissibility function analysis in WSUs and then transmitted to the host computer.

As described in Rytter [12], damage detection can be classified as four levels:

- Level 1: Determination that damage is present in the structure
- Level 2: Determination of the geometric location of the damage
- Level 3: Quantification of the severity of the damage
- Level 4: Prediction of the remaining service life of the structure

Above-mentioned literatures integrate damage detection algorithms with WSS to determine the existence of damage, i.e. level 1 damage detection, or the locations of damage, i.e. level 2 damage detection. There is no WSS which integrates damage detection algorithms and achieves level 3 damage detection of a structure.

In this paper, the authors propose to integrate the frequency response function change method (FRFCM) [13] with WSS to not only detect the presence and location of damage but also estimate the extent of damage, i.e. level 3 damage detection. This is contributed by the advantage of the FRFCM where enough equations to assess locations and extent of damage of a structure can be acquired by using frequency response functions (FRFs) at a few frequencies. To calculate FRFs, one only needs the frequency spectrum segments calculated from measurement in each sensing nodes using FFT algorithm. Without transmitting the whole time-history, only a short array composed of selected frequency spectrum segments is transmitted between the wireless sensing networks. The frequency spectrum segments can be selected at the frequencies close to the eigenfrequencies of the system since the signal to noise ratio of these Fourier spectra is much higher than others. The proposed decentralized strategy which integrates the

FRFCM with WSS is accomplished and then validated via a scaled 6-story steel building structure on a shaking table. Potential energy efficiency gained by the proposed decentralized strategy is discussed. Further modification of hardware in the purpose of minimizing energy consumption of WSUs is beyond the research scope of this study.

2. Implementation of the FRFCM on WSS

2.1 Wireless sensing units

The academic prototype of WSU developed by Wang [14] is employed here to realize the on-line level-3 damage detection. This prototype has been applied to both structural health monitoring [15] and structural control [16, 17] successfully. Figure 1 shows the overall hardware design of the WSU prototype with an optional off-board auxiliary module for conditioning analog sensor signals. The key parameters of the prototype wireless sensing unit are summarized in Table 1. The main WSU (shown in the top part of Figure 1) consists of three functional modules: sensor signal digitization, computational core, and wireless communication. The sensing interface converts analog sensor signals on multiple channels into 16-bit digital formats. The digital data is then transferred to the computational core by a high-speed serial peripheral interface (SPI) port. Abundant external memory (128 kB) is associated with the computational core for local data storage and analysis. The Maxstream 24XStream wireless modem, operating on the 2.4 GHz wireless band is used for peer-to-peer communication between WSUs and between WSUs and the host computer. The auxiliary sensor signal conditioning module (shown in the bottom part of Figure 1) is designed to assist adjusting analog sensor signals prior to digitization.

2.2 The frequency response function change method

The frequency response function change method (FRFCM) derived from the motion of equation of a shear building subjected to a ground motion both before and after damage is capable to detect the location and extent of damage [13]. The damage identification equation of the FRFCM is presented as:

$$\boldsymbol{\tau}_d(\omega)\Delta\boldsymbol{\kappa} = (-\omega^2\mathbf{M} + i\omega\mathbf{C}_1 + \mathbf{K})(\mathbf{T}_d(\omega) - \mathbf{T}(\omega)) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}_1$ and $\mathbf{K}$ denotes the $n \times n$ mass, damping and stiffness matrices, respectively; $\mathbf{T}(\omega)$ and $\mathbf{T}_d(\omega)$ denote the frequency response function matrix between the input ground acceleration vector and the response displacement vector for the intact and damaged system, respectively; $\Delta\boldsymbol{\kappa}$ denotes the variation of story stiffness of a shear building as

$$\Delta\boldsymbol{\kappa} = [\Delta k_1 \quad \Delta k_2 \quad \dots \quad \Delta k_n]^T \tag{2}$$

and $\boldsymbol{\tau}_d(\omega)$ denotes the matrix composed of components in $\mathbf{T}_d(\omega)$ as:

$$\boldsymbol{\tau}_d(\omega) = \begin{bmatrix} T_{d1}(\omega) & T_{d1}(\omega) - T_{d2}(\omega) & & & 0 \\ 0 & T_{d2}(\omega) - T_{d1}(\omega) & & \ddots & \\ & & \ddots & & \\ & \ddots & & T_{d(n-1)}(\omega) - T_{d(n-2)}(\omega) & T_{d(n-1)}(\omega) - T_{dn}(\omega) \\ 0 & & & 0 & T_{dn}(\omega) - T_{d(n-1)}(\omega) \end{bmatrix} \tag{3}$$

where $T_{dp}(\omega)$ presents the p^{th} component in $\mathbf{T}_d(\omega)$.

The only unknown in equation (1) is the vector $\Delta\boldsymbol{\kappa}$. The system matrices of the intact system, *i.e.* mass matrix, damping matrix and stiffness matrix, and the FRFs both before and after damage are required to solve equation (1). In order to obtain the well-estimated system matrices of the intact system, one can construct a finite element model of the structure and modify it to acquire well-estimated system matrices by model updating techniques. Alternatively, the subspace identification technique proposed by Xiao et al. [18] is a very useful tool to obtain the well-estimated system matrices. Once the system parameter matrix $\mathbf{A}$ and output matrix $\mathbf{C}$ have been obtained by the subspace identification algorithm from the measured data, the system damping and stiffness matrices can be obtained for acceleration sensing as:

$$\begin{bmatrix}\mathbf{K} & \mathbf{C}_1\end{bmatrix} = -\mathbf{MCR}^{-1}, \quad \mathbf{R} = \begin{bmatrix}\mathbf{CA}^{-2} \\ \mathbf{CA}^{-1}\end{bmatrix} \tag{4}$$

For velocity sensing or displacement sensing, similar equations can be utilized. This technique needs a reasonable system mass matrix which can be obtained from a finite element model of the system. It has been derived that for obtaining the ratio of the story stiffness variation, the mass matrix of a shear building structure is not necessary to be known [19]. The system matrices in this research are obtained by the subspace identification technique with assuming a diagonal mass matrix as described in the following sections.

For a certain frequency ω_j, there are $2n$ equations (separating real parts and imaginary parts) with n unknowns of the story stiffness variations. To reduce the error due to noise in signals, it is suggested to use m different frequencies around each eigenfrequency and get $2n \times m$ equations for each eigenfrequency because the signal-to-noise ratios around structural eigenfrequencies are higher. And the predicted variations of story stiffness are determined as weighted mean of the results obtained using frequencies around each eigenfrequency according to a results-similarity-criterion. The results-similarity-criterion weights the identified story stiffness variations obtained by each mode according to their similarity to the median value of each story as shown in the following equations:

$$\Delta\hat{\kappa}_i = \sum_{j=1}^{p} \Delta\kappa_{ij} \times w_{ij} \tag{5}$$

$$w_{ij} = \exp(-2(\Delta\kappa_{ij} - \Delta\hat{\kappa}_i)^2 / (\sigma_i)^2) \tag{6}$$

$$\sigma_i = \sqrt{\sum_{j=1}^{p} (\Delta\kappa_{ij} - \Delta\tilde{\kappa}_i)^2} \tag{7}$$

where $\Delta\hat{\kappa}_\iota$ represents the weighted identified stiffness variations of the i^{th} story; $\Delta\kappa_{ij}$ represents the identified stiffness variations of the i^{th} story using frequencies around mode j; w_{ij} represents the weighting determined by the similarity measurement result of each $\Delta\kappa_{ij}$; σ represents the standard deviation between the identified stiffness variations $\Delta\kappa_{ij}$ and the median of identified stiffness variations $\Delta\tilde{\kappa}_i$; p represents the number of identified modes. It has been shown that more reliable results can be obtained without the interference of numerical errors caused by measurement noise [13].

2.3 Integrating WSS with the FRFCM

With the system matrices and also the FRFs of the intact system written in the host computer of a WSS, the rest information needed for damage detection of the monitored structure is some segments of FRFs around the structural eigenfrequencies. On the other hand, because each wireless sensing unit is equipped with a computation core which enables it to transform the measured time-history to the Fourier spectrum and also identify the possible structural eigenfrequencies, the segments of FRFs around the structural eigenfrequencies can be calculated and transmitted automatically to the host computer. Therefore, the FRFCM is chosen to be integrated with the WSS to realize on-line damage localization and quantification.

The on-line damage detection procedure and data broadcast between the WSUs and the host computer are described as follows. After the acceleration time-history $y_i(t)$ is measured in the i^{th} WSU, the Fourier spectrum $Y_i(\omega)$ is calculated by an embedded FFT algorithm. A set of p eigenfrequencies of the structure in the i^{th} WSU, $\bar{\boldsymbol{\varpi}}_i = [\bar{\varpi}_{i1}, \bar{\varpi}_{i2}, \cdots, \bar{\varpi}_{ip}]$, is determined by an embedded peak-picking algorithm which selects the peaks of the Fourier spectrum smoothed by an embedded smoothing algorithm. The frequency set $\bar{\boldsymbol{\varpi}}_i$ selected in each WSU is then transmitted wirelessly to the host computer. The most probable set of the system eigenfrequencies $\bar{\varpi}_{system}$ is decided by taking the median of each set of peaks in the host computer and then broadcasted to all the n WSUs. The i^{th} WSU then transmit a set of Fourier spectrum $\tilde{\mathbf{Y}}_i(\tilde{\boldsymbol{\varpi}}_{system})$ around the system eigenfrequencies back to the host computer. Note that the frequency set $\tilde{\boldsymbol{\varpi}}_{system}$ contains not only the system eigenfrequencies $\bar{\varpi}_{system}$ but also 10 adjacent frequencies around them. After the host computer receives the selected frequency spectrum segments from all the WSUs, the FRF segments are estimated by dividing cross-power spectrum between the structural response and input excitation by the auto-power spectrum of the input excitation. With the system matrices and FRFs of the structure in reference state written in the host computer, the variations of story stiffness matrices $\Delta\boldsymbol{\kappa}$ can be calculated using these FRF segments by equation (1) and equations (5) to (7). Since the necessary information for FRFCM to detect damage of the structure could be accessed automatically right after a ground excitation, e.g. a train passing or an earthquake, on-line damage detection could be achieved. A graphical representation of the implementation of the FRFCM on a wireless sensing system can be found in figure 2. In order to realize the integration of the FRFCM and the WSS, the state machine which controls operating, computing and communicating of the WSUs was designed and coded. The FFT, peak-picking and smoothing algorithms described more explicitly in section 3.2 were also coded and embedded in the WSUs.

3. Experimental validation

3.1 Experimental setup

A 1/4-scale 6-story steel building structure (figure 3) was employed here to perform experimental validation of the proposed wireless on-line damage detection operation scheme. As shown in figure 3, the 6-story 1/4-scale structure consisted of a single bay with 1.0m×1.5m floor area with uniformly 1.0 m story height. The size of column and beam was 150mm×25mm (rectangular section) and 50mm×50mm (L-section), respectively. The beam-floor connection was welded, and the floor-beam connection and the floor-column connection were bolted. The dead load was simulated by lead-block units fixed on the steel plate of each floor, and the total mass of each floor of the target structure was 862.85 kg, except the mass of the roof floor was 803.98 kg. The stiffness of the bracing system was controlled by a small connecting plate (named as “CP”) whose size was 100mm×10mm with clear height 196mm (figure 4).

To imitate damage of the structure, the connecting plates of some of the stories were removed. Because the connection of the connecting plates was designed as bolted, the bending shape of the plate should be between double-curvature and single-curvature. The story-stiffness reduction ratios after the connecting plate were removed assuming the behavior of the plates as double-curvature and single-curvature were calculated. The mean value of these two values was -37.3% and was chosen as a reference value to check with the experimental results.

In order to investigate the feasibility of the proposed wireless sensing system, totally 4 different damage cases (see table 2) under El Centro earthquake excitation in the X direction were studied. Case W1 was the baseline test and no damage was introduced. Case W2 was another baseline test to see if the FRFCM may give false alarm. Case W3 and Case W4 simulated the single and multiple damages respectively by removing the connecting plates in the designated stories. The peak ground acceleration is controlled less than 0.05 g because larger excitation may loosen the bolted connecting plates, which makes the extent of damage unpredictable. Note also that in real application where structure behavior under strong earthquakes may become nonlinear, only the response in the end of the whole time-history should be used to estimate the damage.

For the wired measurement system of the shaking table facility, Setra141-A accelerometers with acceleration range of ±4 g and a noise floor of 0.4 mg were employed. Multiple Pacific Instrument Series PI660-6000 data acquisition chassis are used in the wired system. The wireless sensing unit was instrumented with the "TOKYO SOKUSHIN Servo Velocity Seismometer" type VSE-15A which was placed in each story including the ground floor. The wireless sensing systems consists of 7 wireless sensing units and 7 VSE-15A sensors. A typical setup of wireless sensing units and sensor as well as associated power supply devices and antennas are shown in figure 5. The VSE-15A was switched to acceleration mode in order to compare the wireless measured acceleration data to the one measured by the data acquisition system of shaking table facility. The analog output voltage of the VSE-15A sensor was -10V~10V, which was offset to 0~5V by the auxiliary sensor signal conditioning module. The sampling rate of both wired and wireless system was 200 Hz.

The typical time-history of the measured acceleration response of both the wireless system and wired system in Case W2 after zero-mean are shown in the left part of figure 6. In general, the wireless-measured data had a good agreement with the wired-measured one. However, take a close look at the data as shown in the right part of figure 6, it is evident that the signal to noise ratio in the wireless-measured data is lower than the one in the wired-measured data, especially for the data measured on the ground floor. Looking at the frequency spectra of the measured wired and wireless data as shown in figure 7, it is noted that the measured data on the ground floor is noisy especially for high frequency range. The extra noise in the wireless measured data may contribute additional errors to the damage detection results using FRFCM.

3.2 Embedded algorithms in the WSUs

The implementation of the FRFCM on WSS as described in the previous section requires the WSUs to equip with a FFT algorithm, a smoothing algorithm and a peak-picking algorithm. The Cooley-Tukey FFT algorithm was embedded in the WSUs. The algorithms for smoothing and peak-picking the Fourier spectrum after taking FFT of the measured data are described here. The triangular smoothing with a weighting function was employed as:

$$\hat{Y}_j = \frac{\sum_{i=-n}^{n} Y_{j+i} \times w_i}{\sum_{i=-n}^{n} w_i} \tag{8}$$

where $w_i = n + i + 1$ if $i \le 0$ and $w_i = i$ if $i > 0$; n denotes the half bandwidth of the weighting function; Y denotes the absolute value of FFT results of the measured data; $\hat{Y}_j$ denotes the absolute value of FFT results after smoothing. The peak of smoothed FFT results $\hat{Y}_j$ was picked if $\hat{Y}_j > \hat{Y}_{j-1}$ and $\hat{Y}_{j+1} > \hat{Y}_j$. For the measured data with length of 4096 points, the half bandwidth of the weighting function n started at 20 and increased by 10 per time if wider bandwidth were required. The bandwidth stopped increasing if 6 peaks or less than 6 peaks were picked. For the 6-story steel building structure, only the FFT results below 20Hz were smoothed. The smoothed FFT results below 0.2 Hz was eliminated to avoid abnormal large value caused by offset of the measured data.

3.3 Damage detection results of FRFCM integrated with WSU

The methodology of the FRFCM requires the system matrices of the intact system and the FRFs both prior and posterior to an occurrence of damage. In order to achieve on-line detection of the stiffness variation ratio of each story by integrating FRFCM with the WSS, necessary information of the 6-story steel building structure in intact state, i.e. the intact system matrices and the intact FRFs, needed to be written in the host computer in advance. In this study, the mass matrix was assumed diagonal with the lumped value of story mass as described in section 3.1. The stiffness and damping matrices of the structure in Case W1 were identified from measured data using the subspace identification technique with the diagonal mass matrix. The FRFs of the 6-story steel building structure in Case W1 and also the system matrices of the structure identified using the measured data in Case W1 were written in the host computer in advance. For Case W2 to W4, the adjacent 11 FFT results around the 6 most probable eigenfrequencies calculated by the WSUs were utilized to calculate FRFs right after the host computer received them from WSUs. With the above-mentioned information ready, the variation of story stiffness can be calculated using equation (1) in the host computer. Comparing to the story stiffness which can be estimated using the components in the identified stiffness matrix of the structure in the intact state, the story stiffness variation ratio can be estimated without establishing a finite element model of the structure.

The bars marked as “Wireless On-Line” in figure 8 show the stiffness variation ratio of each story estimated on-line using the wireless-calculated FFT results transmitted from WSUs. For Case W2 with no damage, no stiffness variations for every stories should be identified. For Case W3 and Case W4, stiffness variation ratio of the stories with connecting plates removed should be close to the reference value, while other stories should be no stiffness variations. For all the three cases, the damage locations are detected successfully with the error of stiffness variation ratio less than 15%. In order to see if the error of stiffness variation ratio is mainly caused by the FFT algorithm embedded in the WSUs, the stiffness variation ratio of each story estimated off-line using the FFT results of the wireless-measured time-history calculated by the FFT algorithm of Matlab software in the host computer are also plotted in figure 8 (marked as “Wireless Off-Line”). Little improvement of the results is achieved if FFT results are obtained using the FFT algorithm in the Matlab software. This demonstrates the robustness of the FFT algorithms embedded in the WSUs. However, if the stiffness variation ratio of each story is estimated off-line using the FFT results of the “wired-measured” time-history, the results of damage localization and quantification improved a lot (marked as “Wired Off-Line” in figure 8). It was concluded that much less error is obtained if wired-measured time-history data are used.

The difference between wireless and wired data may be mainly contributed by the hardware difference including power supply devices of sensors, type of sensors and data acquisition system, etc. Nevertheless, the feasibility of the proposed idea to achieve level 3 damage detection by integrating the FRFCM with WSS is verified.

4. Potential energy efficiencies gained from integrating FRFCM with WSS

In order to illustrate the potential energy efficiencies of WSUs gained from integrating FRFC with WSS, both the energy consumption of the traditional centralized strategy and the proposed decentralized strategy were measured off-line for 10 times respectively after the experiment. The latency of calculating and transmitting data of WSUs was obtained by collecting time-stamp data from the WSUs. The current of each stage was measured by the National Instrument's (NI) CompactRIO (cRIO) Control and Acquisition System with NI9227 current input module [20].

Since measurement of raw time-history data are necessary for both strategies, the energy consumption of this part is not taken into account in this study. The calculated energy consumption of the traditional centralized strategy, E_1, only includes the energy consumption for transmitting the raw time-history from the WSU back to the host computer. The calculated energy consumption of the proposed decentralized strategy, E_2, includes the energy consumption for computing the FFT, smoothing and peak-picking in WSUs as well as the energy consumption for transmitting of calculated data. If E_2 is less than E_1, then there is an advantage of energy efficiencies contributed by the integration of FRFCM and WSS.

With each data point requiring 2 bytes of memory, a 4096-point time-history record occupies 8192 bytes. The centralized strategy needs the WSU to transmit these data together with some overheads to the host computer. This required the wireless module transmitting the raw time-history data for 4.668 sec in average. With average current 181.942 mA and internally voltage at 5 V, the energy consumption E_1 for transmitting the raw time-history equaled to 4.299 J. On the other hand, the decentralized strategy incurred 22.234 sec in average for its computation stage which the centralized strategy did not need. With average current 24.473 mA and internally voltage at 5 V, the energy consumption for the computation stage equaled to 2.721 J. However, the data aggregation greatly reduced the data to be transmitted from 8192 bytes to 540 bytes including 528 bytes of FFT results and 12 bytes of location of frequencies. This required the wireless module transmitting for 0.390 sec in average and therefore consumed 0.339 J of energy. As a result, the energy consumption of the proposed decentralized strategy, E_2, equaled to 3.060 J, which is only 71.2% of E_1. This illustrated the advantage of energy efficiencies associated with FRFCM integrated with WSS. Note that the data received by the host computer using the proposed decentralized strategy are already the required segments of FFT results instead of the raw time-history data.

Since in this case the computation of embedded algorithms consumed a lot of the energy for the proposed decentralized strategy, a low-power microcontroller with higher operational rate can achieve even more energy efficiency. Lynch et al. [21] has already demonstrated the potential to greatly reduce energy consumption of computing engineering analyses within a WSU by a two-microcontroller design. Besides a lower-power controller in charge of general operation of a WSU, the additional microcontroller can be specially chosen to execute embedded engineering analyses with little energy consumption. The energy to calculate FFT of 4096 points data is only about 1% of the energy to transmit the raw data in their case. Alternatively, employing single low-power microcontroller which can execute signal processing required by the embedded engineering analyses with high efficiency can replace two-microcontroller design and achieve even higher system robustness. This demonstrates that carefully design of hardware of a WSU can greatly improve energy efficiency gained by exploiting collocated computing resources of WSUs. In addition, customized hardware and power management can further achieve optimized energy efficiency of a WSU. The development of hardware in the future brings unlimited possibility to design a more energy-efficient WSU for structural health monitoring purpose. In this study, only the potential energy efficiency gained by integrating FRFCM with WSS is demonstrated. The design of WSU to achieve optimized energy efficiency is beyond the research scope of this study.

5. Discussions and conclusions

A WSS for structural damage detection application is developed in this research. The WSS is integrated with the FRFCM in order to achieve level 3 damage detection and take advantage of collocated computing resources of WSS at the same time. A 6-story steel building structure instrumented with the developed WSUs is tested on a shaking table to validate the proposed decentralized approach. The experimental results demonstrate that the proposed approach works well for both single and multiple damage scenarios. The potential energy efficiency gained by the proposed approach is illustrated using the experimental case study as an example. Further energy efficiency of the proposed decentralized strategy can be achieved by customized design of hardware and energy management of WSUs.

For comparison, other approaches related to the same idea which integrate damage detection algorithms with wireless sensors and at the same time reduce overall power consumption by reducing the amount of data to be transmitted are compared to the proposed approach. The prototype of WSUs, damage detection methods, damage detection levels, embedded engineering analysis algorithms, structural features transmitted from WSUs of these approaches are summarized in table 3. Among them, it is evident that the proposed WSS is the only one which can achieve level 3 damage detection. The accomplishment of performing on-line level 3 damage detection by integrating the FRCM and WSS is the major contribution of this paper.

Because the major energy efficiency contributed by a decentralized strategy for WSUs depends on the reduction of data for transmitting, the reduction order of the transmitted data using different approaches is estimated. The amount of data transmitted from WSUs using different approaches is estimated with assuming 4096 time-history length, 6 modes, 6 DOFs and 30 AR coefficients for all cases. The reduction order is then calculated by dividing these amounts by the one using traditional centralized wireless approach. For example, if the raw time-history is transmitted, the reduction ratio is 10^0; if only 6 modal frequencies with floating number format are transmitted, the reduction ratio is 10^{-3}. The reduction order of the data transmitted from the WSUs using different approaches are also listed in table 3. The reduction order of the proposed decentralized strategy is about 10^{-2} which allows great potential of energy efficiency provided a low energy consumption of computation in WSUs.

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Table 1: Key performance parameters of the wireless sensing unit.

Design Parameter	Specification
Computing Core	
Microcontroller	8-bit RISC[a] architecture, up to 16MIPS[b] throughput at 16MHz
Flash Memory	128K bytes
Internal SRAM[c]	4K bytes
External SRAM	128K bytes
EEPROM[d]	4K bytes
Power Consumption	30mA active, 55µA standby
Wireless Transmission	
Operating Frequency	ISM 2.4000 - 2.4835 GHz
Data Transfer Rate	19.2 kbps
Communication Range	Up to 180m indoor, 5km at line-of-sight
Power Consumption	150mA transmitting, 80mA receiving, 26µA standby
Sensing Interface	
Sampling Precision and Rate	16bit, Up to 100kHz
Analog Sensor Channels	4

[a] RISC: reduced instruction set computer.
[b] MIPS: million instructions per second.
[c] SRAM: static random access memory.
[d] EEPROM: electrically erasable programmable read-only memory.

Table 2. Cases of experimental study (“CP” represents the connecting plates; “R” represents removing of connecting plates).

	Case Number			
Story number	**W1**	**W2**	**W3**	**W4**
6	CP	CP	CP	CP
5	CP	CP	CP	CP
4	CP	CP	CP	CP
3	CP	CP	CP	R
2	CP	CP	CP	CP
1	CP	CP	R	R

Table 3. WSS with embedded engineering analyses for damage detection.

PERFORMANCE ATTRIBUTE	Straser and Kiremidijan (1998) [2]	Tanner et al. (2003) [3]	Caffrey et al. (2004) [4]	Lynch et al. (2004) [5]	Hackmann et al. (2008) [9]
WSU PROTOTYPE	WiMMS	Motes	Wisden	dual-core prototype by Lynch	Imote2
DAMAGE DETECTION METHOD	normalized Arias intensity	SPC	modal frequencies & signal energy	AR-ARX	DLAC
EMBEDDED ENGINEERING ANALYSIS	-	cross-correlation coefficients	FFT	AR, ARX residual	FFT, PPA, FPCF
DATA TRANSMITTED FROM WSU	time-energy profile	Damage Indicator	modal frequencies & modal signal energy	AR coefficients & Damage Indicator	modal frequencies
DATA REDUCTION ORDER	10^{-1}	10^{-4}	10^{-3}	10^{-2}	10^{-3}
DAMAGE DETECTION LEVEL	level 2	level 1	level 1	level 2	level 2

* assuming 2 Bytes for one raw data; 4 Bytes for one engineering data (e.g. frequencies, FFT results, mode shapes, AR coefficients, Damage Indicator)

Table 3. WSS with embedded engineering analyses for damage detection (continued).

PERFORMANCE ATTRIBUTE	Nagayama et al. (2009) [8]	Hackmann et al. (2010) [10]	Wang et al. (2010) [11]	This paper
WSU PROTOTYPE	Imote2	Imote2	mobile sensing node	wireless sensor prototype by Wang
DAMAGE DETECTION METHOD	stochastic DLV	ASHFM /ASFM	transmissibility function analysis	FRFCM
EMBEDDED ENGINEERING ANALYSIS	FFT, SVD, complex Eigensolver, quick sort, complex matrix inverse	FFT, PPA, FPCF, CSD, SVD	FFT	FFT, smoothing, PP
DATA TRANSMITTED FROM WSU	raw time-history (partial sensors), Damage Indicator	modal frequencies & mode shapes	Fourier spectrum (interested range**) & Damage Indicator	modal frequencies & Fourier spectrum (close to modal frequencies)
DATA REDUCTION ORDER*	10^{-1}	10^{-2}	10^{-1}	10^{-2}
DAMAGE DETECTION LEVEL	level 2	level 2	level 2	Level 3

* assuming 2 Bytes for one raw data; 4 Bytes for one engineering data (e.g. frequencies, FFT results, mode shapes, AR coefficients, Damage Indicator)

** assuming 1/5 frequency range is interested

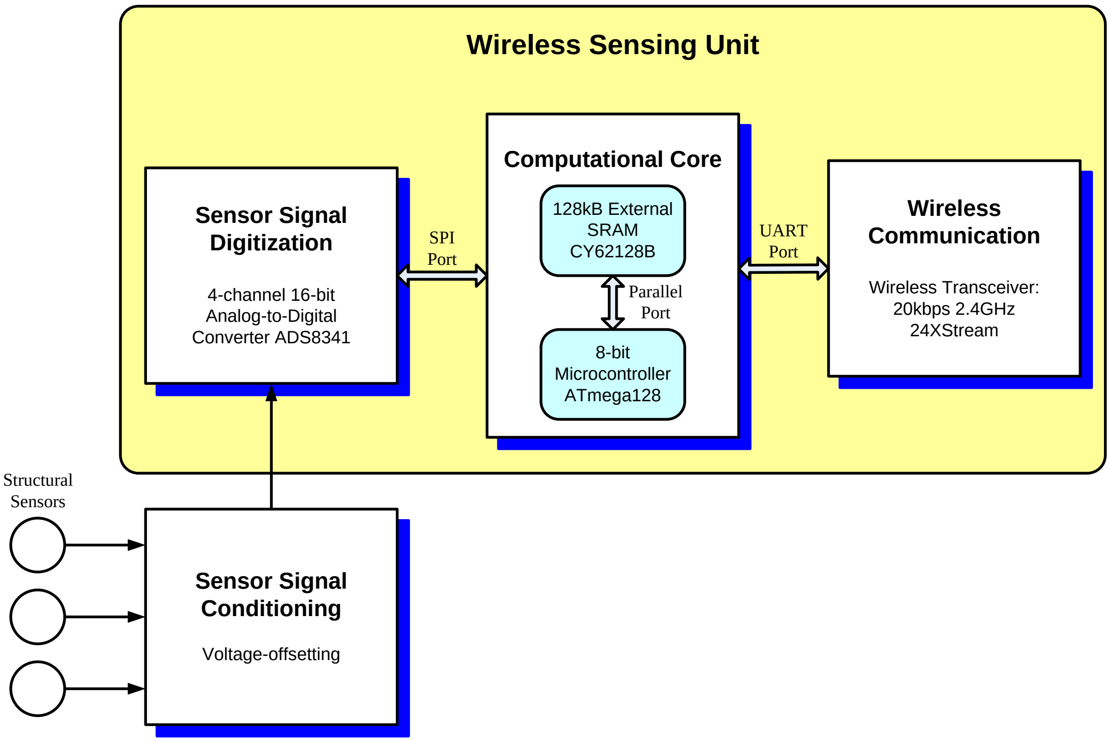

Figure 1. Functional diagram detailing the hardware design of the wireless sensing unit.

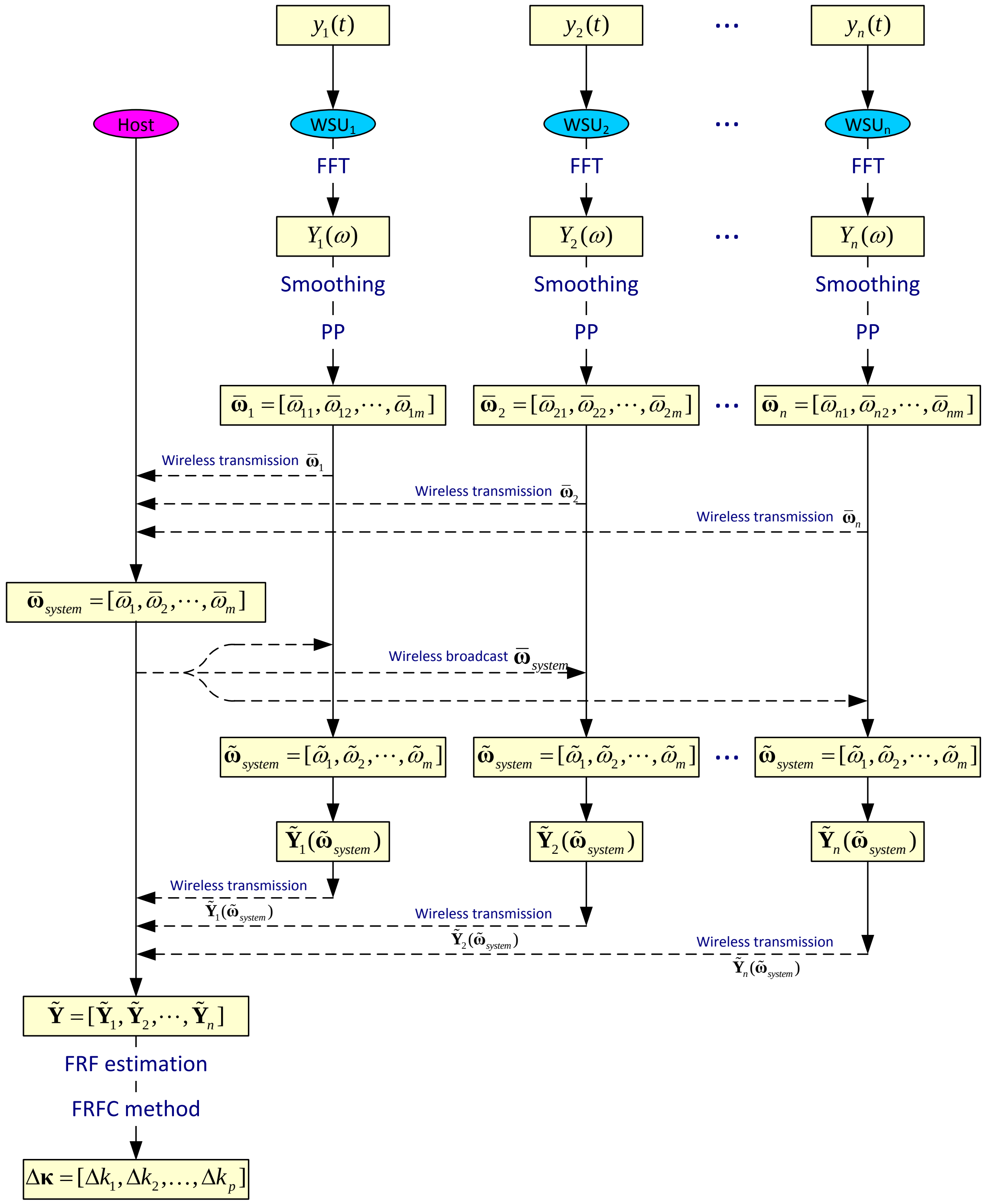

Figure 2: Implementation of the FRFCM on a wireless sensing system.

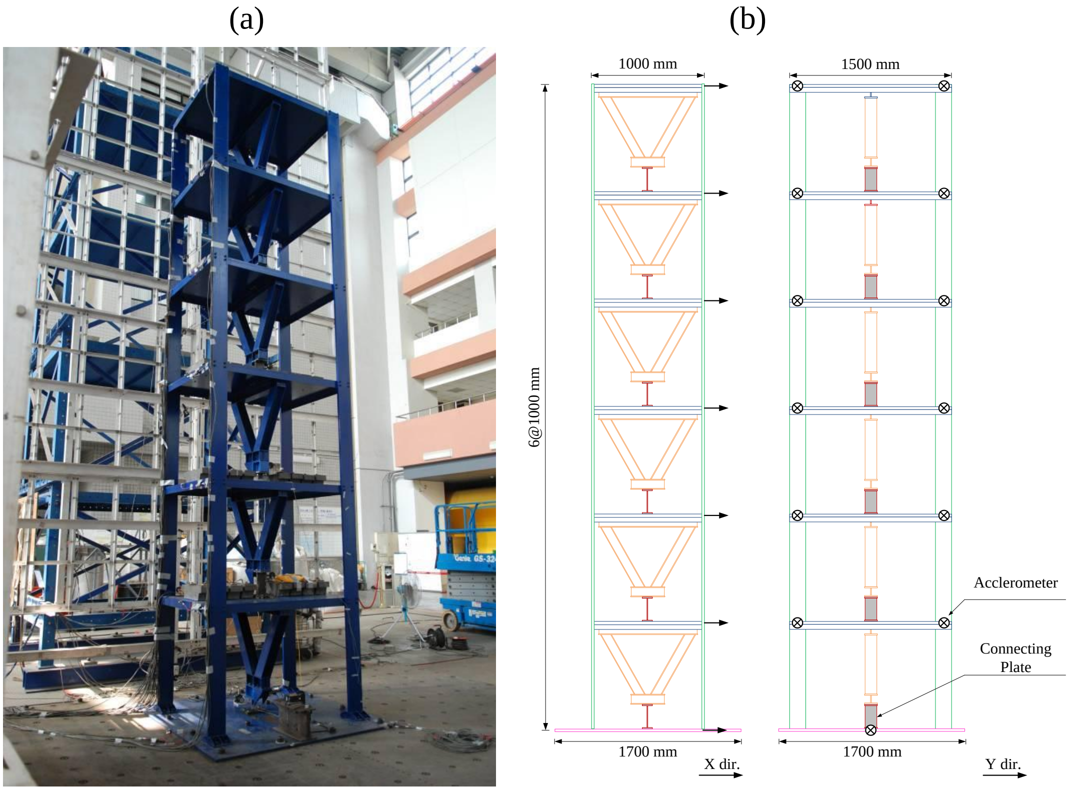

Figure 3. A 1/4-scale 6-story steel building structure: (a) an overview and (b) plane views.

Figure 4: Close view of the bolting connection of the connecting plates.

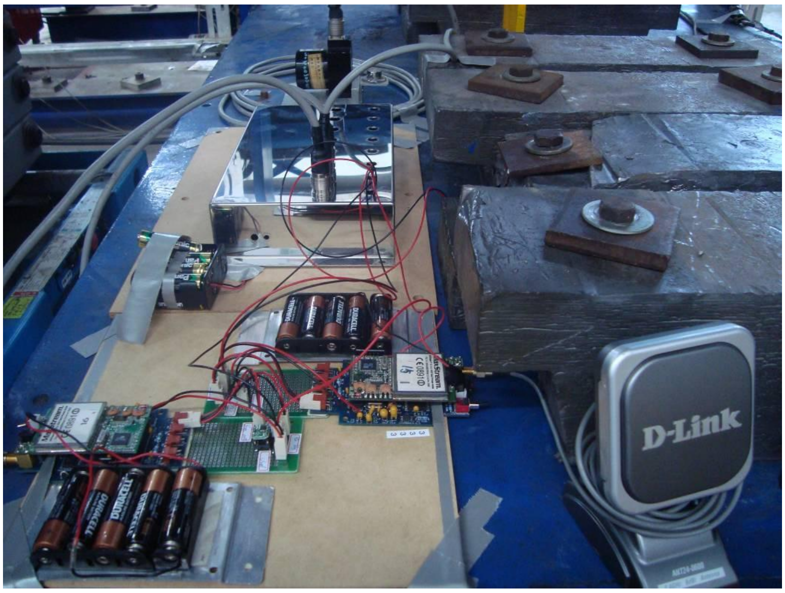

Figure 5. Close view of the wireless sensing units, power supply devices, antennas and sensors.

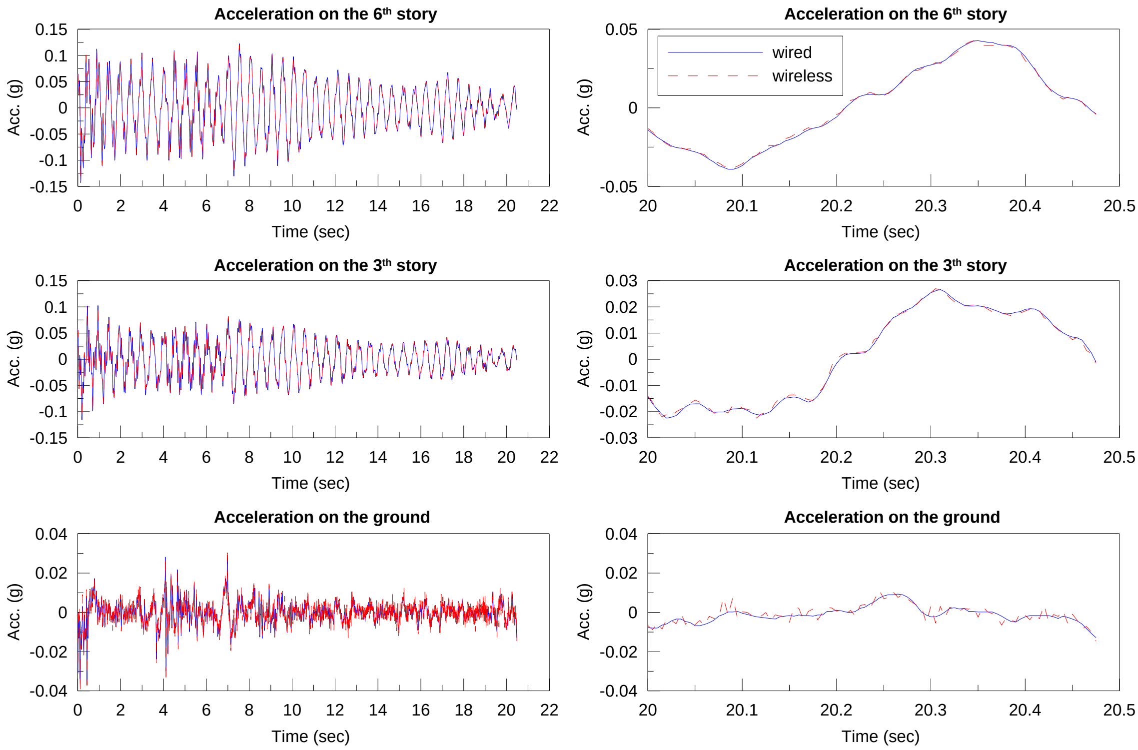

Figure 6: Measured time-history of wireless and wired sensor data. Left: whole time-history. Right: close view.

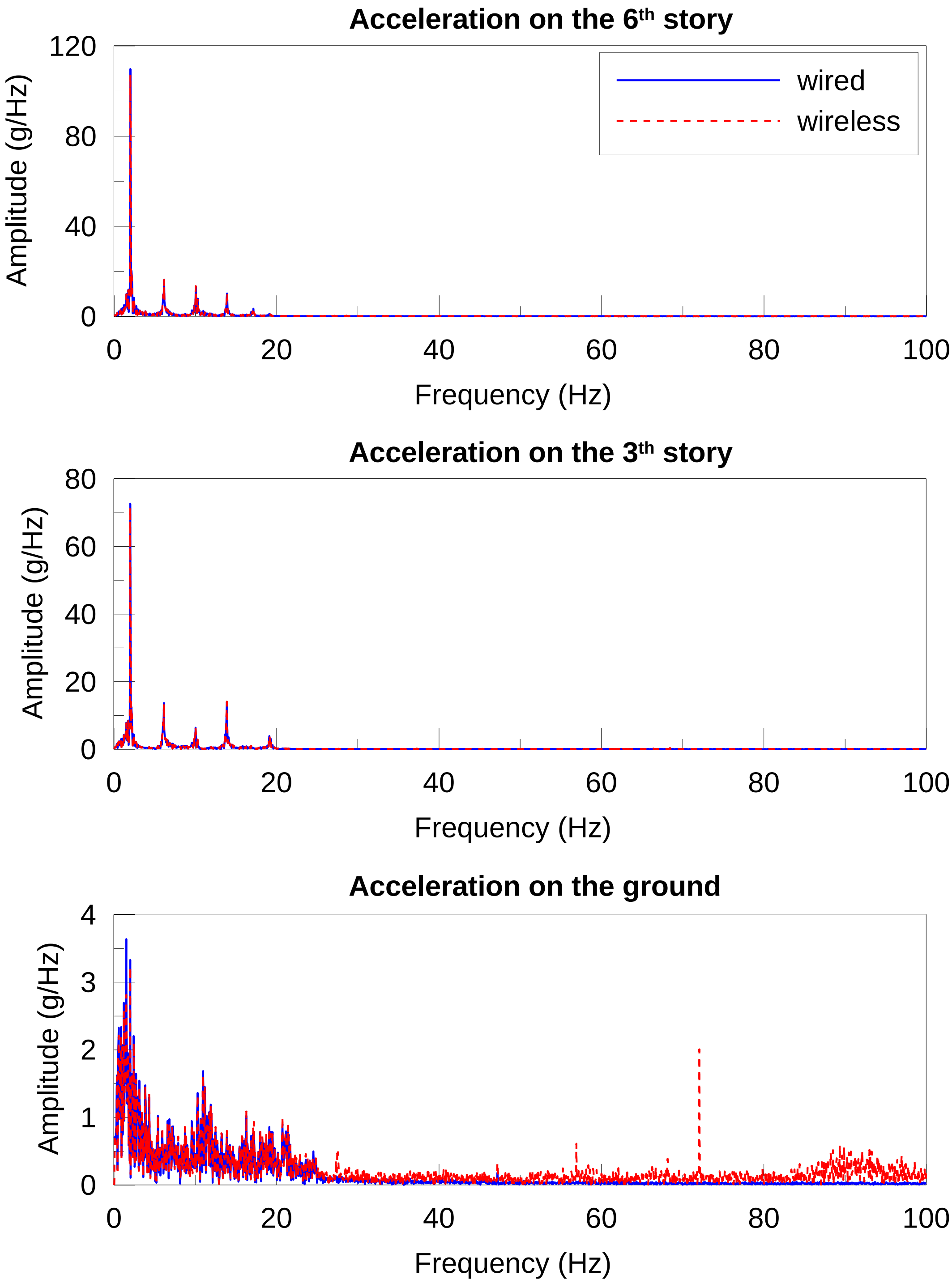

Figure 7: FFT results of wireless and wired sensor data.

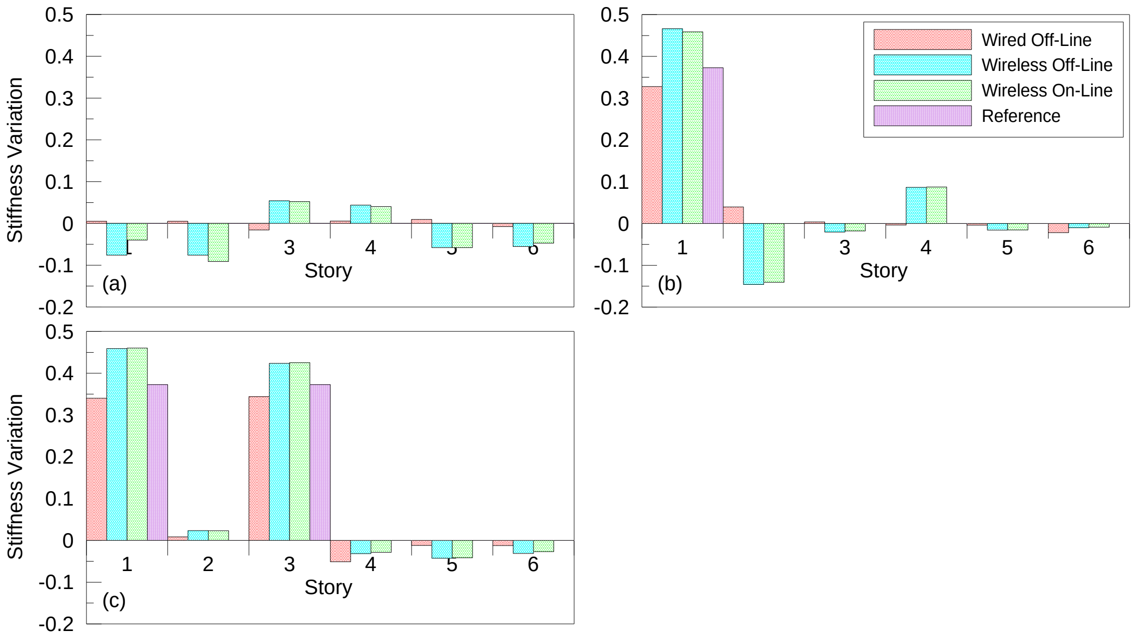

Figure 8. Comparison among identified story-stiffness variation ratio obtained by wireless on-line, wireless off-line and wired off-line. (a) Case W2; (b) Case W3; (c) Case W4.