A damage detection algorithm integrated with a wireless sensing system

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Abstract. In this study, the authors propose a frequency response function change method (FRFCM) which can be integrated with a wireless sensing system to detect damage of a building structure. The FRFCM was derived based on motion equations under a ground excitation both before and after a structure is damaged. The advantage of FRFCM is that only the frequency response functions of some frequency ranges around natural frequencies of a structure are needed to detect the location and extent of a damage. On the other hand, the wireless sensing units have the calculation ability to transform the measured time series to the frequency spectrum using the fast Fourier transform (FFT) algorithm. Therefore, only a few frequency bands of the frequency spectrum in the wireless sensing units are necessary to be delivered to the wireless server, instead of the whole measured time series. By doing so, the transmit power consumption of a wireless sensing unit is greatly reduced, hence increasing the feasibility of on-line damage detection using wireless sensing system based on structural vibration signals. The proposed idea was validated in a shaking table test of a 6-story steel building structure in a laboratory. In order to detect damage on-line automatically via a wireless sensing system, a FFT algorithm and a automatic peak-peaking algorithm for selecting natural frequencies of a structure were imbedded into the wireless sensing units. The damage extent of each story of the structure was displayed on the screen of the host computer automatically after the transmit of fragments of Fourier spectrum from wireless sensing units was done.

1. Introduction
The vibration-based damage detection technique is a promising field in structural health monitoring. The damage to a structure may be detected through the variation of the structural features such as natural frequencies, modal damping, mode shapes, modal strain energy, frequency response functions (FRFs), etc. Sohn et al. [1] and Carden and Fanning [2] presented review papers of global damage detection methods and vibration-based damage detection methods for structures, respectively. The FRFs has been applied to model updating or damage detection for various structures. Wang et al. [3] proposed a damage detection algorithm based on nonlinear perturbation equations of receptance FRF data and applied it to a frame structure. Lee and Shin [4] presented a damage detection algorithm applied to a cantilever beam and improved the effectiveness with a reduced-domain based method. Santos et al. [5] proffered a FRF sensitivities based damage detection algorithm to a laminated structure. Ren and Beards [6] tried to identify the joint properties of a structure using FRF data, and introduced a criterion to reduce the effects of the measurement errors. Xu and Wu [7] proposed a
damage detection algorithm based on the relationship between the FRF and mode shapes and applied it to a cable-stayed bridge structure. Furukawa and Otsuka [8] proposed a statistical damage detection method using uncertain FRFs and applied it to a building structure. All the above mentioned FRF-based damage detection approaches must generate artificial excitations at one or some DOFs on the structure. However, artificial excitations for a civil structure are usually expensive or impractical because of large scale. Ground excitations powered by an earthquake or traffic seem to be a possible alternative provided the amplitude of the ground excitation is much larger than the other excitation sources. Therefore, the frequency response function change method (FRFCM) to detect damage locations and extents of a shear building under ground excitation was developed [9].

On the other hand, 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 [10]. Researchers have utilized the decentralized parallel computing resources in the wireless sensing systems by employing local data processing algorithms in the wireless sensing units for structural health monitoring purpose. Some of them focus on the application of identifying system dynamic parameters such as natural frequencies, damping ratios and mode shapes [11, 12]. Others focus on integrating wireless sensing systems with damage detection approaches by embedding processing algorithms in wireless sensing units to extract necessary system features in local sensor nodes for damage assessment. However, damage detection algorithms that take advantage of decentralized parallel computing resources in the wireless sensing systems are currently limited in the literature. Tanner et al. [13] apply a statistical process control 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 wireless sensing unit. 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 a electromagnetic shaker are processed locally on a microprocessor integrated with the wireless module and an alarm will be triggered automatically if an outlier is indicated. Lynch et al. [14] 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 test structure using a wireless sensing system. The coefficients of an AR model is calculated in the wireless sensing units and transmitted to the host computer. The residual error of the ARX model of the measured data computed in the wireless sensing units is used to determine the presence of damage in the structure. The energy efficiency gained from local data interrogation is also explored in detail. The same damage detection algorithm is later successfully applied to detect damage of nearly full-scale single-story reinforcement-concrete frames [15]. Gao et al. [16] apply a flexibility-based damage detection method to assess local health condition of a truss-structure. Adjacent wireless sensors are grouped together as a community via a hierarchical strategy. Damage locating vectors are computed in each community using the flexibility matrix constructed using modal parameters identified from local measured data. Damage indicators based on change of damage locating vectors are used to determine the occurrence of local damage simulated by replacing elements with smaller ones.

Above-mentioned literatures integrate damage detection algorithms with wireless sensing systems to determine the existence and/or the locations of damage of a structure. In this paper, the authors propose to integrate the FRFCM with wireless sensing systems to not only detect the presence and location of damage but also estimate the extent of damage. This is contributed by the advantage of the FRFCM where enough equations to assess damage of a structure can be acquired by using frequency response functions (FRFs) at a few frequencies. The integration of the FRFCM with a wireless sensing system is realized and then validated via a 6-story steel building on a shaking table. The energy efficiency gained by the proposed wireless sensing system to detect damage is also illustrated.

2. Methodology
2.1. Frequency response function change method

Let $\ddot{U}(\omega)$ be the Fourier spectrum of the measured ground acceleration vector. The equation of motion with $n$ degrees of freedom under a ground excitation $U(\omega)$ in frequency domain is

$$
(-\omega^2 M + i\omega C_i + K)X(\omega) = -ML\ddot{U}(\omega)
$$

where $X(\omega)$ is the Fourier spectrum of displacement response vector; $M$, $C_i$, and $K$ represents the $n \times n$ mass, damping and stiffness matrices, respectively; $L$ represents the loading vector. The displacement vibration response can be represented as

$$
X(\omega) = T(\omega)\ddot{U}(\omega)
$$

where $T(\omega)$ denotes the frequency response function matrix between the input ground excitation vector and the response displacement vector for the intact system as

$$
T(\omega) = (-\omega^2 M + i\omega C_i + K)^{-1}ML
$$

It is assumed that the mass and damping matrices are unchanged after the system is damaged. Therefore the frequency response function matrix $T_d(\omega)$ for the damaged system is

$$
T_d(\omega) = (-\omega^2 M + i\omega C_i + K_d)^{-1}ML
$$

where $K_d$ is the stiffness matrix of the damaged structure. Multiply both sides of equation (3) and equation (4) by $-\omega^2 M + i\omega C_i + K$ and $-\omega^2 M + i\omega C_i + K_d$, respectively. And then subtracts equation (4) from equation (3), equation (5) is obtained as

$$
KT(\omega) - K_d T_d(\omega) + (-\omega^2 M + i\omega C_i)(T(\omega) - T_d(\omega)) = 0
$$

The change in the stiffness matrix and the change in FRFs due to damage are defined as

$$
\Delta K = K_d - K
$$

and

$$
\Delta T(\omega) = T_d(\omega) - T(\omega)
$$

, respectively. Substituting equation (6) and equation (7) into equation (5) yields the damage identification equation

$$
\Delta KT_d(\omega) = (-\omega^2 M + i\omega C_i + K)\Delta T(\omega)
$$

Let $R(\omega)$ denotes the right hand side of the damage identification equation as

$$
R(\omega) = (-\omega^2 M + i\omega C_i + K)\Delta T(\omega)
$$

Therefore equation (8) becomes

$$
\Delta KT_d(\omega) = R(\omega)
$$

The term $\Delta K$ is the variation of stiffness matrix and can be represented as a sum of each elemental matrix multiplied by a reduction factor ($\Delta K = \sum_j \alpha_j K_j$). However, such a representation needs that the element matrices are known or well-updated. In order to circumvent the troublesome model updating procedures to obtain a finite element model with acceptable accuracy, the authors try to solve the variation of element stiffness matrices by only assuming the geometry relationship between the elemental matrices and the system matrix, without assuming the value of each elemental matrix.
Considering an one-dimensional shear building with \( n \) degrees of freedom for example, the system stiffness matrix is assumed to be the form

\[
K = \begin{bmatrix}
k_1 + k_2 & -k_2 & 0 \\
-k_2 & k_1 + k_3 & -k_3 & \ddots \\
& \ddots & \ddots & \ddots \\
0 & \cdots & k_{n-1} + k_n & -k_n \\
\end{bmatrix}
\] (11)

Because we have specified the form of the stiffness matrix, the left hand side of equation (10) can be rearranged to allow the variation of elemental stiffness components to be assembled in a vector and then be rewritten as

\[
\tau_j(\omega) \Delta \kappa = \Delta K \tau_j(\omega)
\] (12)

where

\[
\Delta \kappa = [\Delta k_1 \ \Delta k_2 \ \ldots \ \Delta k_n]^T
\] (13)

and

\[
\tau_j(\omega) = \begin{bmatrix}
T_{d1}(\omega) & T_{d2}(\omega) - T_{d1}(\omega) & 0 \\
0 & T_{d2}(\omega) - T_{d1}(\omega) & 0 \\
& \ddots & \ddots & \ddots \\
0 & \cdots & T_{d(n-1)}(\omega) - T_{d(n-2)}(\omega) & T_{d(n)}(\omega) - T_{d(n-1)}(\omega) \\
\end{bmatrix}
\] (14)

where \( T_{dp}(\omega) \) presents the \( p \) th component in \( T_d(\omega) \). Substituting equation (12) into equation (10) and separating the complex FRFs into real and imaginary parts, equation (10) becomes

\[
\begin{bmatrix}
\Re \tau_j(\omega) \\
\Im \tau_j(\omega)
\end{bmatrix} \Delta \kappa = \begin{bmatrix}
\Re R(\omega) \\
\Im R(\omega)
\end{bmatrix}
\] (15)

For a certain frequency \( \omega_j \), there are \( 2n \) equations with \( n \) unknowns to be solved. To reduce the noise effects and ill-posed problem, one may use \( m \) different frequencies and get \( 2nxm \) equations and then solve them by a least-squares approach. Solving equation (15) gives the variations of elemental stiffness components without assuming the value of the baseline elemental stiffness matrices. The procedure to obtain equation (12) can be automated in a way similar to the development of the finite element model of the system [17].

After the variations of elemental stiffness components in equation (13) are obtained by solving equation (15), the stiffness reduction ratio of the \( i \)th element can be obtained as \( \frac{\Delta k_i}{k_i} \). Note that because \( k_i \) is not known analytically if no FE model is constructed, here the components in the identified stiffness matrix using equation (11) can be utilized to calculate the stiffness reduction ratio.

In summary, the FRFs of the system prior and posterior to damage as well as the system matrices including the mass matrix, damping matrix and stiffness matrix of the undamaged structure are required to solve equation (15). However, to obtain all the well-estimated or well-updated system matrices individually is not an easy task. Alternatively, one can obtain the well-estimated system matrix (i.e. \( -\omega^2 M + i\omega C + K \)) instead of to obtain the well-estimated mass matrix, damping matrix and stiffness individually. In other words, the individual mass matrix, damping matrix or stiffness matrix is not necessary to be close to the true one, but only the system matrix composed of these matrices is necessary to be close to the true one. This can be achieved by using the subspace
identification technique to evaluate the system matrix with acceptable accuracy. Once the system parameter matrix $A$ and output matrix $C$ have been obtained from the subspace identification algorithm with output-only data or input-output data, the system damping and stiffness matrices can be obtained for acceleration sensing as [18]

$$
[K \ C_i] = -M C R^{-1}, \quad R = \begin{bmatrix} C A^{i-1} \\ C A^{i-1} \end{bmatrix}
$$

(16)

For velocity sensing or displacement sensing, similar equations can be utilized.

Because enough equations to obtain the least squares solution in equation (15) can be acquired by using FRFs at a few frequencies. The FRF estimation [19] can be calculated with the frequency spectrum segments calculated by fast Fourier transform (FFT) algorithm for measurement in each sensing unit. 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 as the frequencies close to the eigenfrequencies of the system since the signal to noise ratio of these Fourier spectra is much higher than others.

2.2. Integrating FRFCM with WSS

In order to integrate FRFCM with WSS, an operation scheme is specially designed as the followings. 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 $n$ eigenfrequencies of the structure in the $i^{th}$ WSU, $\bar{\omega}_i = [\bar{\omega}_1, \bar{\omega}_2, \cdots, \bar{\omega}_n]$, 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 $\bar{\omega}_i$ selected in each WSU is then transmitted wirelessly to the host computer. The most probable set of the system eigenfrequencies $\bar{\omega}_{system}$ is decided in the host computer and then broadcasted to all the WSUs. The $i^{th}$ WSU then transmit a set of Fourier spectrum $\tilde{Y}_i(\bar{\omega}_{system})$ back to the host computer. Note that the frequencies set $\bar{\omega}_{system}$ contains not only the system eigenfrequencies $\bar{\omega}_{system}$ 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. The variations of elemental stiffness matrices $\Delta \kappa$ can be calculated using these FRF segments by equation (15). Since the necessary information for FRFCM to detect damage of the structure could be accessed automatically right after a ground excitation, i.e. a train passing or an earthquake, on-line damage detection could be achieved.

3. Experimental Validation

3.1. Wireless Sensing Units

The prototype of wireless sensing unit developed by Wang et al. [20] was employed here to realize the on-line damage detection operation scheme. This prototype was applied to structural health monitoring successfully [15]. Figure 1 shows the overall hardware design of the prototype wireless sensing unit with an optional off-board auxiliary module for conditioning analog sensor signals. The main wireless sensing unit (shown in the top part of the figure) consists of three functional modules: sensor signal digitization, computational core, and wireless communication. The auxiliary sensor signal conditioning module (shown in the bottom part of figure 1) assists offsetting analog sensor signals prior to digitization. For the key parameters of the prototype wireless sensing unit, please refer to [20]. The wireless sensing system has been specially designed for applications in structural monitoring and damage detection.
3.2. Experimental Setup

A 1/4-scale 6-story steel building structure (figure 2) was employed here to perform experimental validation of the proposed wireless on-line damage detection operation scheme. As shown in figure 2, 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 “B3”) whose size was 100mm×10mm with clear height 196mm.

To imitate damage of the structure, the original connecting plate of the bracing system was 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 was 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 methodology, totally 4 different damage cases (see table 1) under El Centro earthquake excitation with peak ground acceleration 0.05 g 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 damage occurring by removing the “B3” connecting plates in the designated stories.

**Table 1.** Cases of experimental study (“B3” represents the connecting plates; “R” represents removing of connecting plates).

| Story number | Case Number |
|--------------|-------------|
| 6            | B3          |
| 5            | B3          |
| 4            | B3          |
| 3            | B3          |
| 2            | B3          |
| 1            | B3          |

For the shaking table wired measurement system, 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 3. 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 system. Becase the analog output voltage of the VSE-15A sensor was -10V~10V, an auxiliary sensor signal conditioning module was designed to transform the original analog output voltage to 0~5V. The sampling rate of both wired and wireless system was 200 Hz.

**Figure 3.** Close view of the wireless sensing units, power supply devices, antennas and sensors.

### 3.3. Imbedded Algorithms in the WSUs

In order to realize the operation scheme which integrates FRFCM with WSS as described in section 2.2, the state machine which controls the operating, computing and communicating of the WSUs was designed, coded and embedded in the WSUs. Besides the state machine, the methodology requires the
WSUs to equip with FFT algorithm, smoothing algorithm and peak-picking algorithm. The Cooley-Tukey FFT algorithm coded by Wang et al. [20] was borrowed here to be 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:

$$\hat{Y}_j = \frac{\sum_{i=0}^{n} Y_{i+j} \times w_i}{\sum_{i=0}^{n} w_i} \quad (17)$$

where $w_i = n + i + 1$ if $i \leq 0$ 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 test structure, only the FFT results below 20Hz were smoothed. Note that $Y$ needs to be padded with zeros for the first few frequencies for the triangular smoothing algorithm. The smoothed FFT results below 0.2 Hz was eliminated to avoid abnormal value caused by offset of the measured data.

3.4. Damage detection results of FRFCM integrated with WSU

The mass matrix was assumed diagonal with the lumped value of story mass. The stiffness and damping matrices of the structure in Case W1 were identified using equation (16). The FRFs of the test structure in Case W1 and also the system matrices of the test structure identified using the data in Case W1 were already written in the host computer. The adjacent 11 FFT results around the 6 most probable eigenfrequencies were utilized to calculate FRFs right after the host computer received them from wireless sensing units. Therefore, on-line detection of the stiffness reduction ratio of each story was implemented by integrating FRFC method with the wireless sensing systems.

The results of stiffness reduction ratio of each story is plotted in figure 4 with bars marked as “Wireless On-Line”. For Case W2 with no damage, no stiffness variations of any story should be identified. For Case W3 and Case W4, stories with connecting plates removed should have stiffness reduction ratio close to the reference value, while other stories should have no stiffness variations. For all the three cases, the damage locations were detected successfully with error of stiffness reduction less than 15%. For the bars in figure 4 marked as “Wireless Off-Line”, the FRFs of the test structure after damage were obtained using FFT results of the wireless-measured time-history calculated in the host computer, instead of the wireless-calculated FFT results calculated in the wireless sensing units. Little improvement of the results was achieved if FFT results were obtained using the DFT algorithm in the Matlab software. However, if the FRFs of the test structure after damage were obtained using FFT results of the wired-measured time-history in the host computer, the results of damage localization and quantification improved a lot (marked as “Wired Off-Line” in Figure 4). Much less error was obtained if wired-measured data were used. The difference between wireless and wired data as shown in figure 4 could 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 integrate FRFCM with WSS to take advantage of collocated computing resources in wireless sensing units was verified.
3.5. Energy efficiencies gained from integrating FRFCM with WSS

The energy consumed by the wireless transmission of raw time-history data $E_i$ is compared to the total energy $E_e$ required by FRFC algorithm in WSU (except the energy for recording raw time-history data). If $E_i$ is less than $E_e$, then there is an advantage of energy efficiencies contributed by the integration of FRFCM and WSS.

Table 2. Approximate current consumption of the wireless sensing unit.

| Component                                | Active Current                        |
|-------------------------------------------|---------------------------------------|
| A/D converter ADS8341                     | 1mA                                   |
| Micro-controller ATmega128 (at 8MHz)     | 15mA                                  |
| SRAM CY62128B                             | 15mA                                  |
| Support electronics                       | 1mA                                   |
| Wireless transceiver 24XStream            | 150mA transmitting, 80mA receiving    |
| Complete wireless sensing unit w/o wireless transceiver | 32mA                                  |
| Complete wireless sensing unit w/ wireless transceiver | 182mA transmitting, 112mA receiving |

3.5.1. Energy consumed by wireless transmission of raw time-history data

The measured time-history and FFT results are stored within the wireless sensing unit memory bank as floating point numbers. With each measurement point requiring 4 byte of memory, a 4096-point time-history record occupies 16,384 bytes of the memory. The 24XStream wireless transceiver is capable of sending data packets with a maximum size of 1462 byte (including 14 byte of overhead per packet). As a result, to wireless transmit these data using the 24XStream wireless transceiver, 12 transmission packets with 16,538 bytes are transmitted wirelessly. The transmission of data takes 6.89 seconds using 24XStream with 19,200 bits/s transfer rate. All the hardware components are internally referenced at 5V. The current consumption of the main components in wireless sensing unit is summarized in table 2 [20]. The complete current consumption of wireless sensing unit in transmitting...
mode is 182mA. Therefore, the energy consumed by the wireless transceiver can be determined as follows:

\[ E_1 = (5V)(0.182A)(6.89s) = 6.27J \quad (18) \]

### 3.5.2. Energy consumed by FRFC algorithms in WSU

The operations required by the FRFCM in wireless sensing unit includes: (i) executing FFT, smoothing and peak-picking algorithms to determine 6 peaks of FFT results in the wireless sensing unit; (ii) transmitting of 6 peaks of FFT results from wireless sensing unit to host computer; (iii) receiving of 6 peaks of FFT results determined in host computer; and (iv) transmitting of adjacent 11 FFT results around the 6 peaks from wireless sensing unit to host computer.

The energy consumed by executing FFT, smoothing and peak-picking algorithms to determine the 6 eigenfrequencies, i.e. \( \bar{\omega} \), depends on the time for smoothing and peak-picking. For determining the 6 peaks of FFT results of the test structure with 4096 points acceleration response, one to five times of both smoothing and peak-picking processes are enough. This means the bandwidth of smoothing is 20 to 60. The time required to calculate FFT is approximately 15 seconds, and the time required to calculate five times of both smoothing and peak-picking is approximately 2 seconds. The complete current consumption of wireless sensing unit without wireless transceiver is 32mA. The energy consumed by the wireless sensing unit for determining the 6 peaks of FFT results can be determined as follows:

\[ E_{2e} = (5V)(0.032A)(15s + 2s) = 2.720J \quad (19) \]

After the 6 peaks of FFT results are determined, the 6 unsigned integers which represent the array of locations of the 6 peaks are transmitted to the host computer wirelessly. Once the most probable set of the system eigenfrequencies is determined in the host computer, i.e. \( \bar{\omega}_{\text{system}} \) in Figure 3-2, the 6 unsigned short integers which represent the array of locations of \( \bar{\omega}_{\text{system}} \) are broadcasted to the wireless sensing units. With each unsigned short integer requiring 2 bytes of memory, the array contains 6 locations of FFT peaks occupies 12 bytes memory. The transmission or receiving of data takes 0.0108 seconds using 24XStream with 19,200 bits/s transfer rate. Following similar calculation algorithm, the energy consumed by the wireless sensing unit for transmitting 6 unsigned integers can be determined as follows:

\[ E_{2t1} = (5V)(0.182A)(0.0108s) = 0.010J \quad (20) \]

And the energy consumed by the wireless sensing unit for receiving 6 unsigned integers (with complete current consumption of wireless sensing unit in receiving mode 112mA) can be determined as follows:

\[ E_{2t2} = (5V)(0.112A)(0.0108s) = 0.006J \quad (21) \]

Once the location of \( \bar{\omega}_{\text{system}} \) is received by the wireless sensing unit, the adjacent 11 FFT results around the 6 peaks are transmitted to the host computer. Both the real part and imaginary part of the FFT results are stored within the wireless sensing unit memory bank as floating point numbers. With each FFT results point requiring 8 byte of memory (both real part and imaginary part), a 66-point FFT results occupies 528 bytes memory. To wirelessly transmit these data using the 24XStream wireless transceiver, only one transmission packet with 542 bytes are transmitted wirelessly. The transmission of data takes 0.23 seconds using 24XStream with 19,200 bits/s transfer rate. Similarly, the energy consumed by the wireless transceiver for transmitting the FFT segments can be determined as follows:

\[ E_{2t2} = (5V)(0.182A)(0.23s) = 0.206J \quad (22) \]

As a result, the total energy \( E_{2} \) required by the FRFCM in WSU is summarized as follows:
which is about 47% of 6.271J. This means that the energy consumed by the wireless sensing unit to perform necessary actions for the FRFC method is less than half of the energy consumed by the wireless sensing unit in transmitting the raw time-history to a host computer without performing any local data interrogation. This illustrates the advantage of energy efficiencies associated with FRFC methods integrated with wireless sensing systems.

4. Conclusions and Discussions
This research work has explored the use of WSS for structural health monitoring applications. The WSUs has been specially designed to integrate with the FRFCM. Not only damage localization but also damage quantification can be achieved by the proposed WSS. The proposed approach takes advantage of collocated computing resources of WSS and reduce the energy consumed by WSUs at the same time. State machine and necessary algorithms for the FRFCM are imbedded into the WSUs to realize the proposed idea. On-line damage localization and quantification of the 6-story steel building structure using the FRFCM integrated with the WSS is successfully accomplished. In the experimental case study, more than 50% energy efficiency of the WSUs is gained by the proposed approach.

It is assumed that the stiffness variation of the structural components is identified from the measured data under constant environmental factors. In practice, the stiffness variations identified at different time fragments always fluctuate with varying environmental factors such as temperature and humidity. The stiffness variation caused by damage may be smeared by these environmental effects. In order to accommodate environmental effects when applying the proposed approach in this paper, data normalization techniques are necessary. Many approaches to tackle the environmental effects when performing damage detection can be found in the literature [21, 22]. The methods which deal with environmental effects by implicitly modelling the underlying relationship between the environmental factors and structural stiffness are recommended to be integrated with the proposed approach. Due to difficulties to simulate environmental change in the laboratory, treating environmental effects is not included in this paper.

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