Embedded transmissibility function analysis for damage detection in a mobile sensor network

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ABSTRACT

Structural health monitoring (SHM) and damage detection have attracted great interest in recent decades, in meeting the challenges of assessing the safety condition of large-scale civil structures. By wiring remote sensors directly to a centralized data acquisition system, traditional structural health monitoring systems are usually costly and the installation is time-consuming. Recent advances in wireless sensing technology have made it feasible for structural health monitoring; furthermore, the computational core in a wireless sensing unit offers onboard data interrogation. In addition to wireless sensing, the authors have recently developed a mobile sensing system for providing high spatial resolution and flexible sensor deployment in structural health monitoring. In this study, transmissibility function analysis is embedded in the mobile sensing node to perform onboard and in-network structural damage detection. The system implementation is validated using a laboratory 2D steel portal frame. Simulated damage is applied to the frame structure, and the damage is successfully identified by two mobile sensing nodes that autonomously navigate through the structure.

Keywords: Embedded computing, transmissibility function analysis, mobile sensor network, damage detection.

1. INTRODUCTION

Large-scale civil structures, such as bridges, dams, and high-rise buildings, may be subjected to severe natural disasters over their operational life spans. To closely monitor the behavior of these structures, the concept of structural monitoring was adopted in the 1960s [1]. Data generated by a structural health monitoring system can provide insight into the performance of a structure over its service period. Traditional structural health monitoring is characterized by centralized systems that employ sensors wired to a centralized data acquisition (DAQ) system. However, the cost of installing a wired structural monitoring system in civil structures can be prohibitive, mostly due to the high costs associated with cable maintenance and installation. For example, an SHM system installed in a low-rise building can cost $5,000 per sensing channel with typical installations [2]. Installing extensive lengths of cables can consume over 75% of the total installation time of an SHM system [3].

To significantly reduce the cost of current cable-based structural monitoring systems, advanced wireless sensing and embedded computing technologies can be adopted as a cost-effective and reliable alternative for current cabled SHM systems. Straser and Kiremidjian [3] investigated the reliability and cost-effectiveness of wireless communications in lieu of extensive cabling for structural monitoring. A comprehensive review of wireless sensors and their adoption in structural health monitoring has been provided by [4]. For example, the wireless SHM platform designed by Wang *et al*. [5] has been successfully validated on a number of bridges, buildings, and wind turbines located in the United States, Taiwan, South Korea, China, and Germany [6-8]. Lynch *et al*. [9] further explored the concept of embedding damage identification algorithms directly into wireless sensing units, harnessing the computational resources of these devices to execute data interrogation algorithms. The embedding of engineering algorithms within the wireless sensing units serves as a means of reducing power consuming wireless communications, which largely increases the battery life of the wireless units. In addition, this decentralized data processing architecture allows a large number of sensing nodes, without burdening the wireless communication channels.

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As a transformative change to wireless sensor networks, the next revolution in sensor networks has been predicted to be mobile sensor networks that implant mobility into traditional sensor networks [10, 11]. In a mobile sensor network, each mobile sensing node can be an autonomous robot equipped with one or multiple smart sensors. The mobile node explores its surroundings and exchanges information with its peers through wireless communication. In our previous research, Lee *et al.* [12] introduced the development and implementation of a flexure-based mechatronic mobile sensing node capable of attaching/detaching sensors onto/from a structural surface. The mobile sensing node has the potential to fulfill functions of negotiating in complex steel structures with narrow sections and high abrupt angle changes. Laboratory experiments demonstrated that data collected by a reference fixed sensor matched well with the data collected by a mobile sensing node. Guo *et al.* [13] conducted further analysis and numerical simulations regarding the compliant mechanism of the flexure-based mobile sensing node.

In recent years, various damage detection algorithms have been developed for identifying the existence of damage in structures [14]. Among these methods, transmissibility function analysis attracted considerable interest due to its effectiveness in damage identification, as well as because the analysis does not require input force measurement. Different aspects of transmissibility function analysis, such as the linearity of structures [15], the nature of input force [16], and the effect of operational and environmental variability [17], have been explored. Based on previous work, transmissibility function analysis is well understood and being adopted in structural damage detection. In our previous research, transmissibility function analysis has been successfully employed to perform damage detection analysis using data collected by the mobile sensing nodes [18].

This study investigates the embedded intelligence of the mobile sensing nodes for autonomous structural damage detection. Transmissibility function analysis is implemented in the computational core of the mobile sensing node, so that the mobile node autonomously identifies structural damage. Section 2 presents an overview of transmissibility function analysis. Section 3 introduces the hardware design of the mobile sensing nodes, and Section 4 describes various aspects of the system software design. Embedded computing algorithms executed by the mobile sensing nodes are adopted for local data processing within a mobile sensor network. Section 5 presents laboratory tests intended to validate the performance of the autonomous damage detection using the mobile sensor network. The last section summarizes this paper and discusses the future research work.

2. OVERVIEW OF TRANSMISSIBILITY FUNCTION ANALYSIS

The equations of motion for an *n*-degree-of freedom (*n*-DOF) linear structure can be formulated as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \tag{1}$$

where $\mathbf{x}(t)$ is the $n\times1$ displacement vector, $\mathbf{M}$ is the $n\times n$ mass matrix, $\mathbf{C}$ is the $n\times n$ viscous damping matrix, $\mathbf{K}$ is the $n\times n$ stiffness matrix, and $\mathbf{f}(t)$ is the $n\times1$ external force vector. If the external force is applied to only the k-th DOF, then $\mathbf{f}(t) = \{0_1, 0_2, \ldots, f_k(t), \ldots, 0_n\}^T$ has only one non-zero entry.

Using Fourier transform, Eq. (1) can be represented in the frequency domain as

$$\mathbf{X}(\omega) = \mathbf{H}(\omega)\mathbf{F}(\omega) \tag{2}$$

where $\mathbf{H}(\omega)$ is the $n\times n$ frequency response function (FRF) matrix. Assuming the external force is applied to only the k-th DOF, the Fourier transform of the input force vector $\mathbf{f}(t)$ is determined as

$$\mathbf{F}(\omega) = \{0_1, 0_2, \ldots, F_k(\omega), \ldots, 0_n\}^T \tag{3}$$

The acceleration vector in frequency domain can be computed from Eq. (2) as

$$\mathbf{A}(\omega) = -\omega^2\mathbf{H}(\omega)\mathbf{F}(\omega) \tag{4}$$

The transmissibility function $T_{ij}(\omega)$ between the output DOF i and reference-output DOF j is defined as the ratio between two frequency spectra $A_i(\omega)$ and $A_j(\omega)$. Letting $\mathbf{h}_i(\omega)$ be the i-th row of $\mathbf{H}(\omega)$, the transmissibility function $T_{ij}(\omega)$ can be computed as

$$T_{ij}(\omega)=\frac{A_i(\omega)}{A_j(\omega)}=\frac{-\omega^2\mathbf{h}_i(\omega)\mathbf{F}(\omega)}{-\omega^2\mathbf{h}_j(\omega)\mathbf{F}(\omega)}=\frac{\mathbf{h}_i(\omega)\mathbf{F}(\omega)}{\mathbf{h}_j(\omega)\mathbf{F}(\omega)} \tag{5}$$

Substituting the $\mathbf{F}(\omega)$ (Eq. (3)) into Eq. (5), T_{ij} is further simplified as

$$T_{ij}(\omega)=\frac{H_{ik}(\omega)}{H_{jk}(\omega)} \tag{6}$$

where $H_{ik}(\omega)$ and $H_{jk}(\omega)$ are entries of the FRF.

An integral damage indicator (*DI*) between DOFs (i.e., locations) *i* and *j* is defined as

$$DI_{ij}=\frac{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^U\right|-\ln\left|T_{ij}^D\right|\right|d\omega}{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^U\right|\right|d\omega} \tag{7}$$

where ω_1 and ω_2 are the lower and upper boundaries of the interested frequency span, $|\cdot|$ denotes the magnitude of a complex number, superscript *U* represents the undamaged structure, and superscript *D* represents the damaged structure. Accordingly, T_{ij}^U represents the transmissibility function of the undamaged structure, and T_{ij}^D represents the transmissibility function of the damaged structure. The damage indicator is defined in the logarithmic coordinate, so the difference among small numbers has a larger influence on the integration. In practice, to reduce the effect of experimental uncertainties, the vibration experiments can be repeated *N* times for both undamaged and damaged structures, then the averaged transmissibility functions are used for calculating the damage indicators:

$$T_{ij}^U=\frac{1}{N}\sum_{k=1}^{N}(T_{ij}^U)_k \tag{8a}$$

$$T_{ij}^D=\frac{1}{N}\sum_{k=1}^{N}(T_{ij}^D)_k \tag{8b}$$

where $(T_{ij}^U)_k$ represents the transmissibility function T_{ij}, computed from the *k*-th repeating test with the undamaged structure between DOFs *i* and *j*; and $(T_{ij}^D)_k$ represents the transmissibility function T_{ij}, computed from the *k*-th repeating test with the damaged structure for DOFs *i* and *j*. If acceleration data are available from the experiments, the transmissibility function from each test is computed according to Eq. (5) as the direct division between the frequency spectra of the acceleration at two DOFs *i* and *j*.

For the repeatability check of the experiments, the repeatability indicator (*RI*) is defined in parallel to the damage indicator. For example, for the undamaged structure, the repeatability indicator is defined as

$$RI_{ij}^U=\frac{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^{U\_odd}\right|-\ln\left|T_{ij}^{U\_even}\right|\right|d\omega}{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^{U\_odd}\right|\right|d\omega} \tag{9}$$

where $T_{ij}^{U\_odd}$ and $T_{ij}^{U\_even}$ are the average transmissibility function among all odd and even group of data sets from the undamaged structure, respectively. Similarly, the repeatability indicators among the data sets of the damaged structure are also defined as

$$RI_{ij}^D=\frac{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^{D\_odd}\right|-\ln\left|T_{ij}^{D\_even}\right|\right|d\omega}{\int_{\omega_1}^{\omega_2}\left|\ln\left|T_{ij}^{D\_odd}\right|\right|d\omega} \tag{10}$$

where $T_{ij}^{D\_odd}$ and $T_{ij}^{D\_even}$ are respectively the average transmissibility functions among all the odd and even group of data sets from the damaged structure.

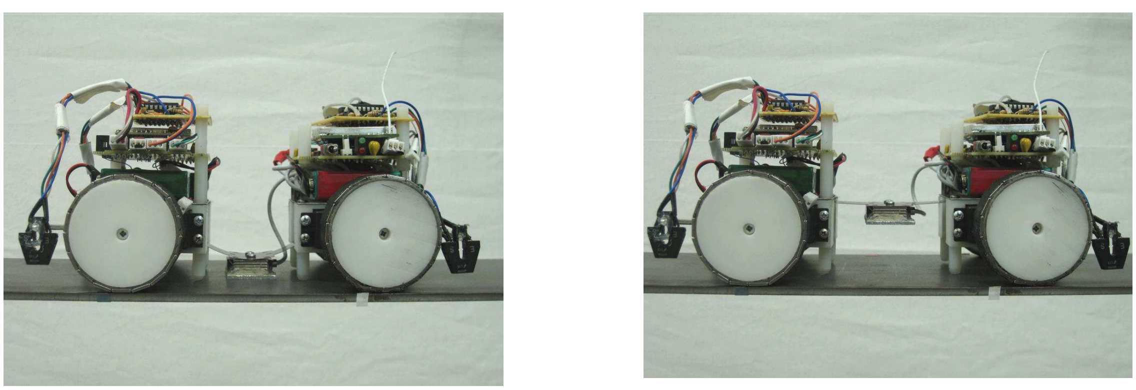
3. HARDWARE DESIGN OF THE MOBILE SENSING NODE

Fig. 1 shows the mobile sensing node developed by [12]. The mobile sensing node consists of three substructures: two 2-wheel cars and the compliant connection beam. Each 2-wheel car contains a body frame, motors, batteries, a wireless sensing unit, infrared (IR) sensors, and Hall-effect sensors with associated hardware circuits. The wireless sensing unit consists of three functional modules: the sensing interface, the computational core, and the wireless communication module [5]. The sensing interface converts an analog acceleration signal into a digital format and transmits data to the computational core, which consists of an 8-bit Atmel ATmega128 microcontroller and an external static random access memory (SRAM) chip. Meanwhile, the computational core communicates through a MaxStream 9XCite wireless transceiver with other wireless sensing units and a central server. To achieve mobility, the microcontroller in the mobile sensing node also commands the motors in real time, based upon real-time motion information provided by the IR and Hall-effect sensors. The IR sensors detect whether the mobile sensing node is moving inside the structural boundary, and the Hall-effect sensors monitor the angular velocities of the magnet wheels. Detailed descriptions on how to ensure the mobile sensing node moves safely on the underlying structural surface can be found in [12].

The overall weight of the mobile sensing node is about 1 kg (2.2 lbs), most of which is contributed by the magnet wheels, motors, and batteries. Powered by onboard batteries, the mobile sensing node can be completely tetherless during operation. Fig. 1(a) and 1(b) show that the compliant connection beam is used to attach/detach the accelerometer onto/from the structural surface. When measurement needs to be made, the two cars are driven towards each other to make the compliant beam buckle downwards to the structural surface. The accelerometer is then firmly attached to the structural surface, as shown in Fig. 1(a). When the accelerometer is to be detached, the two cars move in opposite directions, lifting the accelerometer away from the surface and straightening the compliant beam, as shown in Fig. 1(b). When the accelerometer is attached to the structural surface, the length of the mobile sensing node is 0.191 m (7.5 in). When the accelerometer is detached, the length of the node is 0.229 m (9 in), the width about 0.152 m (6 in), and the height about 0.091m (3.6 in).

4. EMBEDDED TRANSMISSIBILITY FUNCTION ANALYSIS

For autonomous damage detection by the mobile sensing system, transmissibility function analysis is embedded into the computational core of the mobile sensing nodes. The system includes one central server and two mobile sensing nodes, one of which serves as the master node and the other as the slave node. The central server is responsible for 1) remotely commanding the two nodes to move to the measurement locations, 2) transmitting the transmissibility function of the undamaged structure to the master node, 3) synchronizing the internal clocks of the mobile sensing nodes, 4) commanding the two nodes to perform data collection, and 5) receiving and storing the damage indicators of the structure. The software written for the mobile sensing system has two parts: computer software for the central server and embedded software for the mobile sensing nodes. Since the central server and mobile sensing nodes (the master and slave nodes) need to communicate frequently with each other, their software must be designed in tandem. Fig. 2 shows



(a) (b)

Fig. 1. Side view of the magnet-wheeled mobile sensing node: (a) accelerometer attachment; (b) accelerometer detachment.

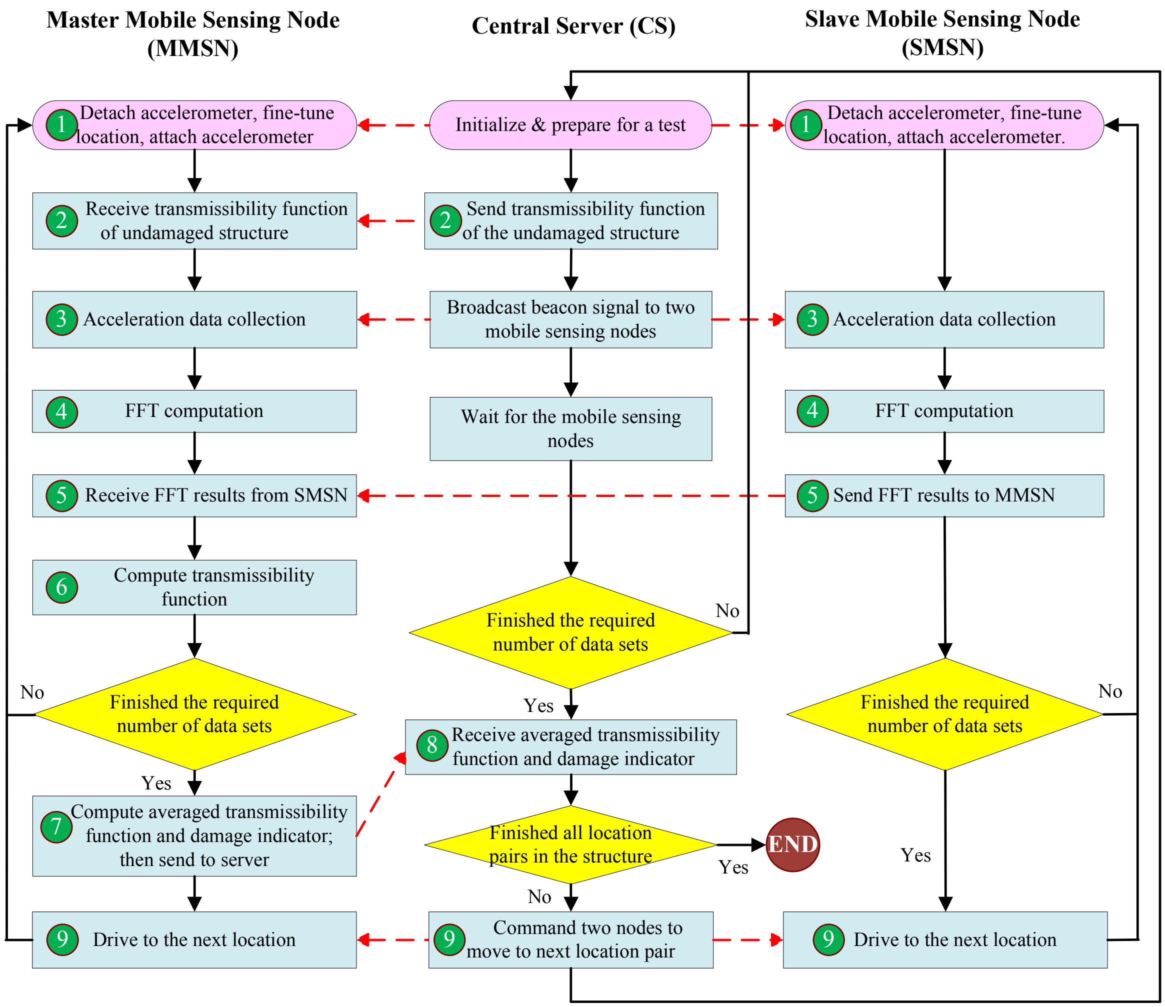


Fig. 2. Flow diagram detailing the procedure for communication between the central server and two mobile sensing nodes.

the flow diagram of the mobile sensing system for structural damage detection, including the central server and two mobile sensing nodes. To achieve a robust performance, state machine concept [19] is employed for the software architecture of both the mobile sensing nodes and the central server.

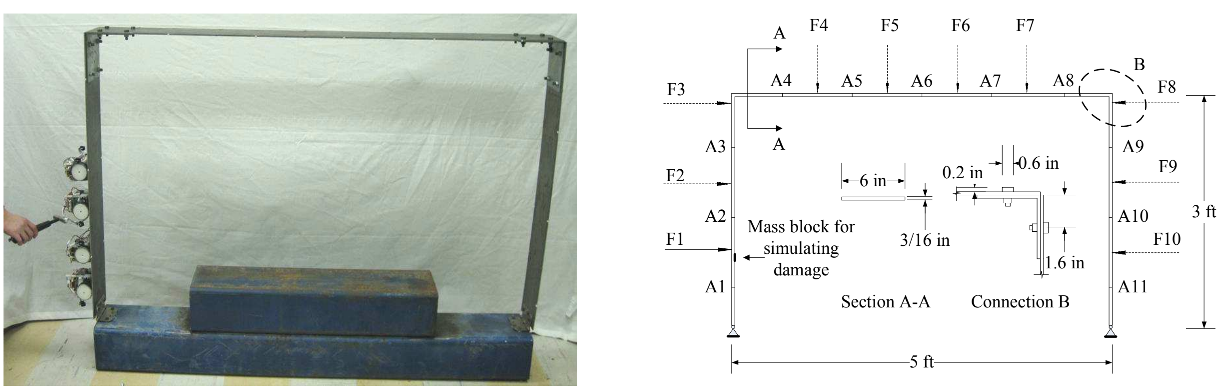
At the beginning of a test, the central server wirelessly commands the two mobile sensing nodes to move to the measurement locations, and then the nodes attach the accelerometers to the structure. When the two nodes are ready to collect data, an initialization packet is sent to the two nodes through wireless communication, which assigns the master/slave roles. The central server also sends the transmissibility functions (between these two locations) of the undamaged structure to the master node. The two nodes then begin to collect acceleration data upon receiving a beacon broadcasted by the central server, so that both nodes start data collection simultaneously. Each mobile sensing node collects data from its associated accelerometer at a specified sampling rate and saves the data temporarily into the onboard memory. Then embedded fast Fourier transform (FFT) is performed by both mobile sensing nodes. FFT results within the interested frequency range are transmitted from the slave node to the master node and stored in the onboard memory. After successful data transmission, embedded transmissibility function analysis is performed by the master node. This process repeats until the required number of data sets is collected at current location pair, after which the averaged transmissibility function and the damage indicator for this location pair are computed by the master node. The damage indicator is then transmitted back to the central server. Afterwards, the server commands the two mobile sensing nodes to move to the next pair of measurement locations, until all required locations pairs on the structure have been covered.

5. VALIDATION EXPERIMENTS

To test the performance of the mobile sensing system for structural damage detection, laboratory experiments are performed on a 2D steel portal frame (Fig. 3a). The span of the portal frame is 1.524m (5 ft) and the height 0.914m (3 ft). The beam and two columns have the same rectangular section area of 0.152m (6 in) $\times$ 0.005m (3/16 in). At the base of the two columns, hinge connections are adopted. The structure is assigned with eleven measurement locations, three of which are on the left column (A1 to A3), three on the right (A9 to A11) column, and the other five locations (A4 to A8) uniformly assigned on the beam (Fig. 3b). A steel mass block of 0.575kg (1.27lb) is bonded to the left column 0.229m (9in) above the hinge joint to simulate reversible damage. In contrast, the mass of the left column is 4.985kg (10.990lb).

The experiments follow the operating procedures explained in the previous section. To take acceleration measurements, the two mobile sensing nodes move to every pair of locations (A1-A2, A2-A3, A3-A4, A4-A5, A5-A6, A6-A7, A7-A8, A8-A9, A9-A10, and A10-A11) in sequence. Each mobile sensing node carries a Silicon Designs 2260-010 accelerometer. As shown in Fig. 3(b), a hammer impact is applied in the middle of two adjacent measurement locations, so that vibration data are recorded by the mobile sensing nodes. Measurements at each location pair are collected for 20 times, for reducing the effects of experimental uncertainties. In other words, the number N in Eq. (8) is equal to 20. Then the averaged transmissibility function is used for calculating the damage indicators, according to Eq. (7).

During the experiments, the sampling rate of the mobile sensing nodes is set at 2,500 Hz. Prior to A2D (analog-to-digital) sampling, the accelerometer signal is conditioned by a low-pass fourth-order Bessel filter. For the embedded FFT computing, a 4,096-point Cooley-Turkey algorithm is implemented in the computational core of the mobile sensing node. At 2,500Hz sampling frequency, the 4,096-point data collection time is about 1.6s. No zero-padding is performed on the time history data. After the FFT computation, only the 100~1,000 Hz frequency range is used to compute the transmissibility function, i.e. ω_1 and ω_2 in Eq. (7) are set to 100 Hz and 1,000Hz, respectively. During the laboratory experiments, the execution time for each numbered step in the flow diagram is illustrated in Fig. 4. The circled numbers refer to those in the flow diagram in Fig. 2.



(a) (b)

Fig. 3. Laboratory steel portal frame for damage detection using mobile sensing nodes: (a) picture of the portal frame; (b) schematic of measurement and impact locations.

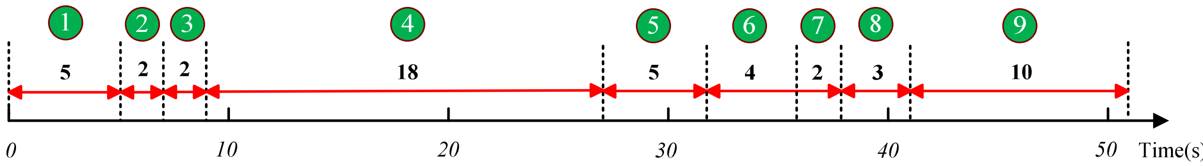


Fig. 4. Execution time for each numbered procedure in the flow diagram (Fig. 2) during the laboratory experiments.

The transmissibility functions computed by the embedded algorithm in the master node are presented in Fig. 5, in magnitude. It is shown that the additional mass block changes the magnitude and peak frequencies of the transmissibility functions. Furthermore, larger difference in the transmissibility functions is observed between location pairs close to the simulated damage location, which is between locations A1 and A2 in Fig. 3(b). Transmissibility functions at locations far away from the damage generally demonstrate very little change between the undamaged and damaged structures.

The damage indicators, which are computed offline by MATLAB and computed onboard by the master mobile sensing node (MMSN), are presented in Fig. 6. The damage indicators computed by MATLAB and MMSN are in close agreement, which indicates that computation by the mobile sensing node is accurate. On the other hand, the results show that the simulated damage between locations A1 and A2 is successfully localized. The figure also presents the repeatability indicators for the undamaged and damaged structures, computed by MATLAB. Compared with the damage indicators, the repeatability indicators are relatively small, suggesting that experimental uncertainties have limited effects to damage detection.

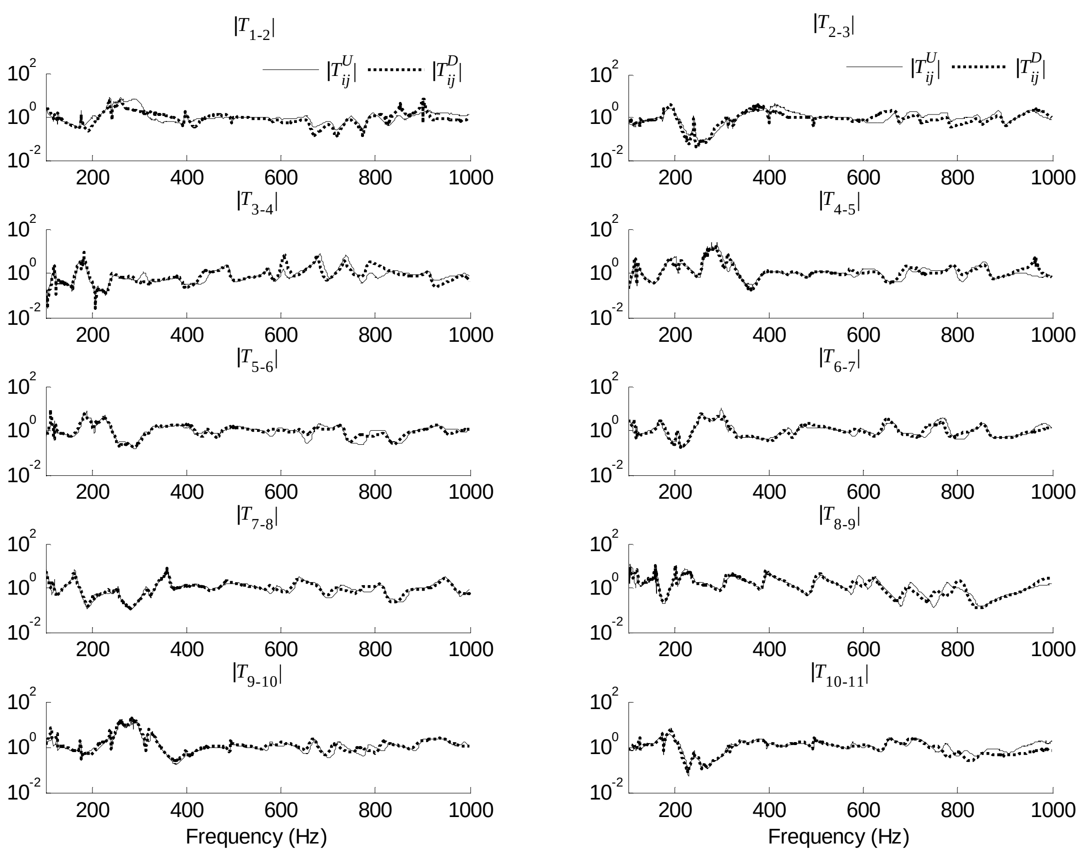


Fig. 5. Comparison between the transmissibility functions of the undamaged and damaged structures computed by the mobile sensing node.

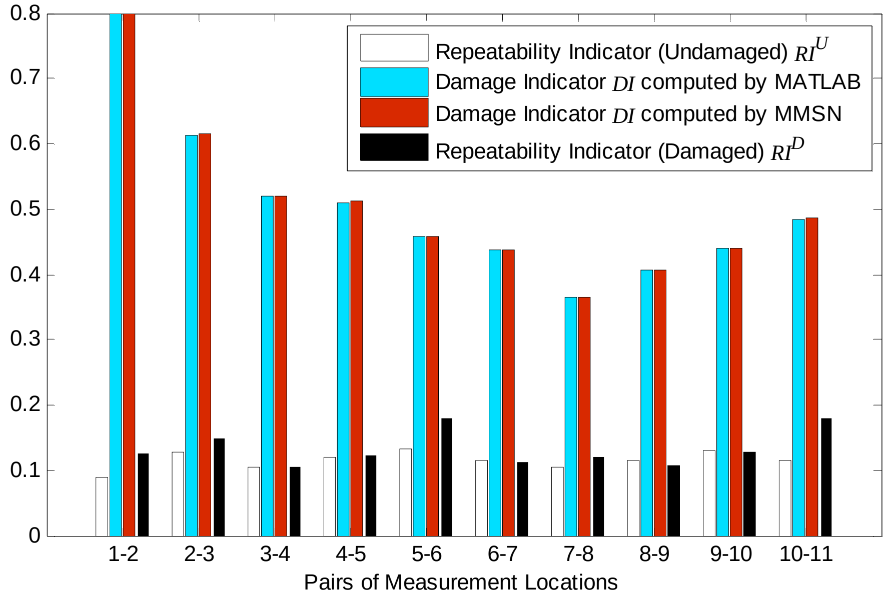


Fig. 6. The damage indicators and repeatability indicators for ten pairs of measurement locations.

6. SUMMARY AND DISCUSSION

This study explores mobile sensing for the autonomous structural damage detection of a laboratory portal frame. The transmissibility function analysis algorithm is embedded in the mobile sensing nodes for onboard analysis. A laboratory portal frame is constructed to validate the performance of the mobile sensing nodes in damage detection. Using acceleration data collected by the mobile sensing nodes, location of the damage is accurately determined through online transmissibility function analysis. The advantage of autonomous damage detection through mobile sensing is thus demonstrated as the high spatial resolution measurement that requires limited number of sensors and little human effort.

Future research will be focused on a number of areas. A great amount of efforts will be needed to make the mobile sensing nodes capable of maneuvering upon more realistic structures built with ferromagnetic materials. In addition, work is also underway in exploring ambient vibration measurement with mobile sensing nodes, as well as in developing a mobile excitation node that can apply small-magnitude impact forces.

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