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A New Type of Intelligent Wireless Sensing Network for Health Monitoring of Long Span Bridges

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ABSTRACT: Structutral health monitoring of long span bridges is important for the safety and maintenance of bridges. In this paper, a new type of wireless monitoring network is proposed for monitoring large span bridges. Hardware design and software architecture of the wireless monitoring system are introduced. The wireless monitoring network has two-level cluster-tree architecture. The software and network architectures proposed emphasize the distributed computational capacity for parallel data processing in the network wireless monitoring network so as to reduce the amount of data transmission. A distributed computing strategy for modal identification of large span bridges is proposed. Numerical example of distribute computing the modal properties of three-span continuous beam illustrates the distributed out-put only modal identification algorithm based on NExT and ERA techniques. The distributed computing strategy can be incorporated into the new wireless monitoring network for automated modal identification of large span bridges.

Keywords: wireless sensing network; intelligent sensor; structural health monitoring; modal identification; ambient vibration.

1 INTRODUCTION

With the development of wireless communication, wireless monitoring systems have been proposed to eradicate the extensive lengths of wires in the tethered systems. Some innovative wireless monitoring systems have been proposed in recent years [1-2]. While wireless sensing network provides an economical data acquisition technology for monitoring large size structures, an enormous advantage of the wireless sensor network over their tethered counterparts is its distributed computational resources collocated with the sensor nodes [2-3]. Such resources can be leveraged to allow the sensor to perform its own data interrogation tasks. The ability of wireless sensors to autonomously collect and analyze data has led to these devices being labeled as “smart” sensor [3]. This capability is particularly attractive within the context of SHM for large size structures. Already, some data processing algorithms have been embedded in wireless sensors for autonomous execution [4-6]. However, all these algorithms are typically been performed independently at sensing node, without direct sharing of data between nodes of a wireless sensing network. These relative simple algorithms are not sufficient for structural identification and damage detection of large span bridges.

In this paper, a new type of wireless sensing units and sensor network is proposed for the heath monitoring of large-size structures. Hardware design and software architecture of the wireless monitoring system are introduced. The sensor network has a two-level cluster-tree architecture with Zigbee communication protocol built on IEEE802.15.4 wireless communication standard. The communication of sensing nodes in a cluster with the cluster head forms the lower level while the communication between the cluster heads forms the upper level [7]. Each cluster head in the network is embedded with some computational algorithm, granting the wireless monitoring network with intelligent characteristics. The software and network architectures proposed emphasize parallel data processing and minimal communication so as to ensure power efficiency.

Some algorithms have been developed for out-put only modal identification as modal parameters are important dynamic properties. However, these algorithms are implemented conventionally in a centralized manner and significant limitations exist for conducting SHM of long span bridges either using wired or wireless sensors [8]. In this paper, a distributed computing strategy for modal identification of large span bridges is proposed to eliminate the burden of transferring a tremendous amount data. A large span bridge is decomposed into smaller substructures. Out-put only modal identification of each substructure is performed based on Natural Excitation Technique (NExT) and the eigensystem realization algorithm (ERA). Identification results of each substructure are then rescaled to construct the modal parameters of the whole structure. Numerical example of distribute computing the modal properties of three-span continuous beam illustrates the distributed out-put only modal identification algorithm. The distributed computing strategy can be incorporated into the new wireless monitoring network for automated modal identification of large span bridges.

2 THE NEW WIRELESS SENSING NETWORK

2.1 Network topology for the wireless sensor network

In the usual STAR network topology, all the sensor units communicate with a central monitoring station. Such an approach solves most of the problems associated with wired systems, but throws up the new problems that are inherent to the wireless systems. For long span bridges spanning several hundred meters to even one thousand meters long, the monitoring system is widespread with dense array of sensors and some of the sensors placed very remotely from the central station. This makes the process of data acquisition difficult as wireless links have limited range. Also, the amount of power required to transmit data over such large distances is quite large [7]. To meet the demands of large network nodes, low complexity, long distance data transmission and low power in wireless senor network for the application of structural health monitoring of large-size structures, a two-level cluster-tree network topology is proposed for the new wireless sensor network as shown in Fig. 1

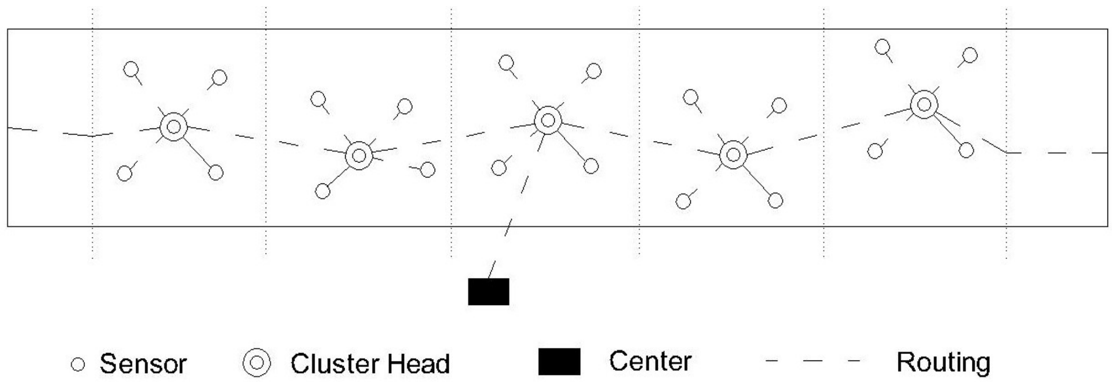

Fig.1: A cluster-tree wireless network topology of the new wireless sensor network

The distributed sensing nodes in a substructure are grouped into a cluster. A cluster head is assigned to each cluster to coordinate the sensing node in its cluster and to collect data from them during monitoring. Communication between the distributed sensing nodes with their corresponding cluster head forms the lower tier and the network of cluster heads forms the upper tier. A cluster head not only serves as a router of the network messages but also possesses computational capabilities with the data collected from the sensing nodes in the cluster. While the new type of wireless sensing network provides an low power topology for long distance data transmission, an enormous advantage of the new wireless sensor network is that it provides parallel computation between the substructures, which is a useful feature particularly attractive within the context of SHM for large size structures., e.g., it can be incorporated with the proposed distributed modal identification for long span bridges.

2.2 Hardware design of the wireless sensing units

Figure 2 show the hardware design of a wireless sensing node and a cluster head. The units mainly consist of six functional modules: 1) sensor interface; 2) signal conditioning module; 3) signal digitization; 4) computational core; 5) wireless communication module; 6) battery management module.

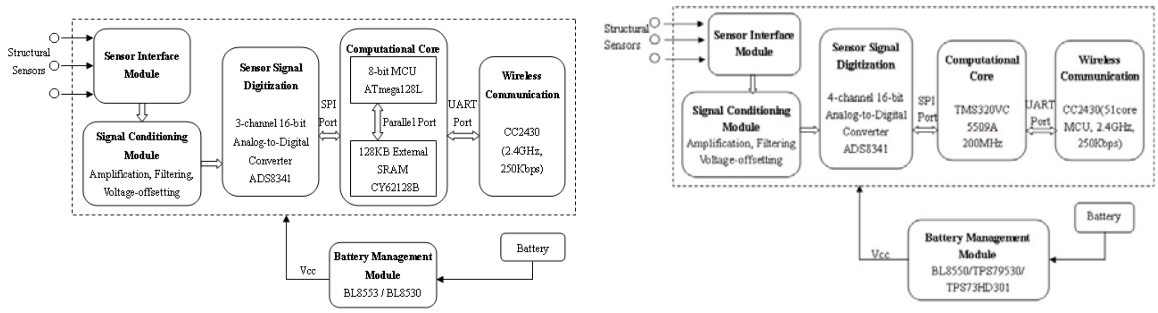

Fig. 2: Hardware structure of sensing node and cluster head in the wireless sensor network

2.2.1 Sensor interface

The sensor interface is responsible for the interfacing of various structural sensors such as accelerometers, strain gains, linear voltage displacement transducer and anemometers that will provide measurements of environmental loads and responses of the structure.

2.2.2 Signal conditioning module

A wireless monitoring system must be capable of recording both ambient and forced structural vibrations. To render the wireless sensors suitable for use in ambient structural vibration studies, a signal conditioner is proposed to condition the voltage output of accelerometers prior to connection to the wireless sensor module is necessary. The three major functions of the circuit board are: Amplification, filtering and Voltage-offsetting.

2.2.3 Signal digitization module

In this design, the wireless sensing unit can support up to 3 structural sensors simultaneously through the Texas Instruments ADS7821 16-bit analog-to-digital (A2D) convertor. The sampling frequency can be up to 100kHz, which is high enough for the structural monitoring application. Each wireless sensing unit can accommodate signals from a set of structural sensors, as long as their outputs are analogy voltages from 0 to 5V. Other signals have been modified by the signal conditioning module.

2.2.4 Computational Core

The computational core of a sensing node is different from that of a cluster head. The difference between a sensing node and a cluster head lies in their computational cores. The computational core of the wireless unit is responsible for executing embedded software instructions for engineering analyses. For a normal wireless sensing node, the 8-bit Atmel ATmega128L AVR microcontroller is selected as the principle component of the computational core. The microcontroller has 128KB of ROM, which is sufficient for storing monitoring software. In addition to ROM, 4kB of SRAM is integrated with the microcontroller; however, this amount of SRAM is insufficient to store all the collected data. An additional 128kB of SRAM (Cypress CY62128B) is interfaced with the microcontroller for the storage of sensor data. A more powerful, high-performance but low-power digital signal processor (DSP) TMS320C5509 with a RAM 256K*16bit, ROM 64K*16bit, and a maximum operating frequency up to 200-MHz clock rate is selected as the computational core of the cluster head for executing the embedded software of the proposed distributed computing of modal identification. TMS320C5509 has low-power consumption as it consumes about 100mW when working at 120MHz.

2.2.5 Wireless communication module

In this design, The Chipcon CC2430 is selected as the wireless transceiver, which is a true System-on-Chip (SoC) solution specifically tailored for IEEE 802.15.4 and ZigBee applications. The CC2430 combines the excellent performance of the leading CC2420 RF transceiver with an industry-standard enhanced 8051 MCU, 32/64/128 KB flash memory, 8 KB RAM and many other powerful features. It enables ZigBee nodes to be built in with very low total bill-of-material costs. The radio operates on the 2.4 GHz radio spectrum with a data rate of 250 kbps. The radio has a range of 10–75m [7].

2.2.6 Battery management module

Battery is the only power source in wireless sensing. During the operation process of the wireless sensing, battery voltage is gradually reduced, which is not able to supply power. For battery maintenance and prolong of the duration time of batteries, a battery management module is designed. As shown in Figs.2-3, the module utilized the BL8530 step-up DC-DC Converter. The converter can start up by supply voltage as low as 0.8V, and capable of delivering maximum 200mA output current at 3.3V output with 1.8V input Voltage.

3 DISTRIBUTED MODAL IDENTIFICATION OF LARGE-SIZE STRUCTURES

Many algorithms have been developed for out-put only modal identification. However, these algorithms are centralized in nature, i.e., out-put data collected by all sensors deployed in a structure are fed into a central station where modal parameters of the whole structure are identified. It is difficult not only to transmit the large amount of output data to the central station but also to conduct modal identification for large-scale structures due to substantial computation. To overcome these difficulties, a distributed computing strategy for modal identification of large span bridges is proposed. A large span bridge is decomposed into smaller substructures. Out-put only modal identification of each substructure is performed based on NExT and ERA techniques.

The basic idea behind the NExT method is that the cross-correlation function between the response vector and the response of a selected reference DOF satisfies the homogeneous equation of motion, provided that the excitation is weakly stationary random process, which is normally the case for ambient excitation, i.e.,

$$M\ddot{R}_{\ddot{X}_{ref}\ddot{X}}(\tau)+C\dot{R}_{\ddot{X}_{ref}\ddot{X}}(\tau)+KR_{\ddot{X}_{ref}\ddot{X}}(\tau)=0 \tag{1}$$

in which M, C, and K are the mass, damping, and stiffness matrices of a substructure, respectively; $\ddot{X}(t)$ is a measured acceleration response in a substructure; $\ddot{X}_{ref}(t)$ is the acceleration response of the reference DOF, which is selected as the overlapped DOF between the substructure concerned with the adjacent one.

Once the homogeneous equation of motion Eq. (1) for the cross-correlation function is formed, ERA can be used to extract the modal parameters of the homogeneous model. A $n(r+1)\times m(p+1)$ Hankel block data matrix can be formed as follows:

$$H(k-1)=\begin{bmatrix} Y(k) & Y(k+1) & \dots & Y(k+p) \\ Y(k+1) & Y(k+2) & \cdots & Y(k+p+1) \\ \vdots & \vdots & \ddots & \vdots \\ Y(k+r) & Y(k+r+1) & \cdots & Y(k+p+r) \end{bmatrix} \tag{2}$$

where n and m=number of measurement stations and reference DOFs in the substructure, respectively; r and p=integers corresponding to the number of block rows and columns, respectively; $Y(k)=n\times m$ matrix of the cross-correlation function which satisfies the homogeneous equation of motion, Eq.(1), and can be written as

$$Y(k)=\begin{bmatrix} y_{1,1}(k) & y_{1,2}(k) & \dots & y_{1,m}(k) \\ y_{2,1}(k) & y_{2,2}(k) & \cdots & y_{2,m}(k) \\ \vdots & \vdots & \ddots & \vdots \\ y_{n,1}(k) & y_{n,2}(k) & \cdots & y_{n,m}(k) \end{bmatrix} \tag{3}$$

in which $y_{i,j}(k)$ is the cross-correlation function $R_{\ddot{X}_{ref}\ddot{X}}(k)$ of DOF i, at the time step k, due to the selection of reference DOF j.

ERA factorizes the Hankel block data matrix, for k=1, using singular value decomposition (SVD)

$$H(0)=PDQ^T=\begin{bmatrix} P_1 & P_2 \end{bmatrix}\begin{bmatrix} D_1 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} Q_1^T \\ Q_2^T \end{bmatrix} \tag{4}$$

where D =diagonal matrix of monotonically non-increasing singular values; and $D_1=N\times N(N\le p)$ diagonal matrix formed by truncating the relatively small singular values, where N=final system order. P_1 and Q_1 are $n(r+1)\times N$, and $m(p+1)\times N$ matrices, that include the first N columns of the original P and Q matrices, respectively. The discrete-time state-space realization matrices for the structural model can be estimated as [9]

$$\hat{A}=D_1^{-1/2}P_1^TH(1)Q_1D_1^{-1/2} \quad ; \quad \hat{C}=E_m^TP_1D_1^{-1/2} \tag{5}$$

where $E_m^T=\begin{bmatrix} I & 0 \end{bmatrix}$, and its size is determined accordingly. Then, from the eigenvalue problem for $\hat{A}$, i.e., $\hat{A}=\hat{\Psi}\hat{\Lambda}\hat{\Psi}^{-1}$, where $\hat{\Lambda}$ and $\hat{\Psi}$ =eigenvalue and eigenvector matrices, respectively, the natural frequencies, ω_i, damping ration, ζ_i, and the mode shapes, $\hat{\Phi}_i$, of the sub-structural model can be found as follows:

$$\omega_i = \sqrt{\sigma_i^2 + \Omega_i^2} \quad ; \; \zeta_i = -\cos\left[\tan^{-1}(\Omega_i / \sigma_i)\right]; \;\; \hat{\Phi}_i = \hat{C}\hat{\Psi}_i \tag{6}$$

in which, $$\hat{\Lambda} = diag(\bar{\sigma}_i \pm j\bar{\Omega}_i) \; ; \; \sigma_i \pm j\Omega_i = \frac{\ln(\bar{\sigma}_i)}{\Delta t} \pm j\frac{\ln(\bar{\Omega}_i)}{\Delta t} \tag{7}$$

and Δt is the sampling period of data records. Once the natural frequencies, damping ration and the mode shapes of each substructure are identified, the frequencies and damping ratios of the whole structure can be estimated from average method. While the mode shapes of the whole structure can be combined from rescaled the local mode shapes of each substructure.

3.1 Numerical example of distributed modal identification of a continuous beam

As an illustration example, distributed modal identification of a continuous beam is shown. The continuous beam shown in Figure 3 has three-spans with the main-span=7.5m and the two side-spans=6m and 4.5m, respectively. Its bending stiffness $EI = 1.11 \times 10^7 \, kN \cdot m$ and the linear density ρ=7850kg/m, respectively. The beam is desecrated into 24 elements with 25 lumped-masses as shown in Figure 3. For distributed computing the modal identification, the beam model is divided into four substructures with element 1-7 being the first substructure, element 7-13, element 13-20, and element 20-25 being the second, third and the last one. The beam is divided into smaller substructures with less DOF so that the proposed cluster head node hardware resources can handle the data and computation.

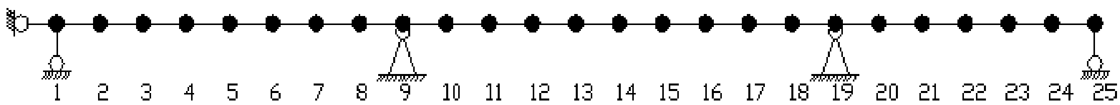

Fig.3: Three-span continuous beam model

The aforementioned distributed computation of modal identification algorithm is applied to identify the frequencies and mode shapes of the three-substructures, in which the overlapped DOFs, i.e., node 7, 13 and 20 are selected as references DOFs, respectively. 3,000 acceleration response data at each DOF are used for distributed modal identification. To validate the accuracy of the distributed modal identification results, FE method is applied to evaluate the modal parameters of the whole beam directly. Identification results are then compared with those by FEM.

Table 1 compares of the first natural frequencies identified by the distributed computing algorithm with those by FEM.

Table 1: Frequencies of the Beam (Hz)

	FE Method	Distributed Identification	Error (%)
1st Frequency	1.2286	1.2061	1.83
2nd Frequency	1.9556	1.9854	1.52
3rd Frequency	3.1236	3.1376	0.45

It is shown that the distributed identification results of the frequencies of the beam are quite accurate.

In Figure 4, distributed identification results of the first three mode shapes of the continuous beam are compared with those by FEM. It is also noted that the results of identified mode shapes are quite accurate

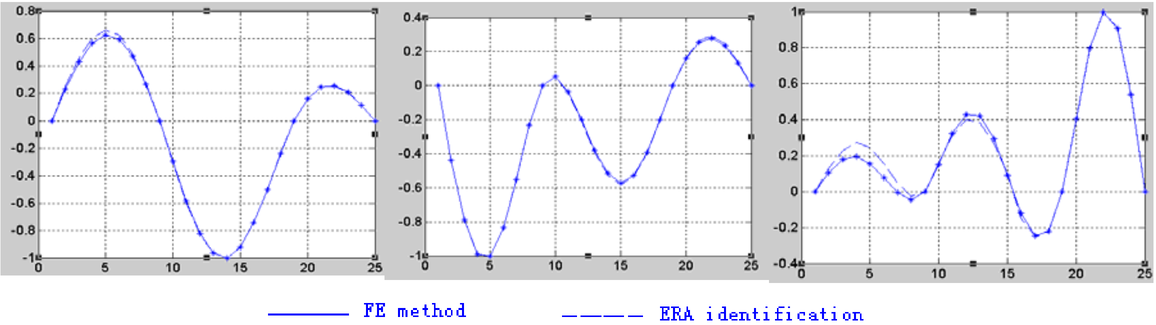

Fig. 4 (a) Fig. 4 (b) Fig. 4 (c)

Fig. 4 (a): Comparision of the 1st mode; Fig. 4 (b): Comparision of the 2nd mode

Fig. 4 (c): Comparision of the 3rd mode shape

4 DISTRIBUTED COMPUTING STRATEGY OF MODAL IDENTIFICATION OF LONG SPAN BRIDGES BASED ON THE NEW WIRELESS SENSING NETWORK.

The distributed modal identification algorithm can be incorporated into the new wireless monitoring network for automated modal identification of large span bridges. As shown by

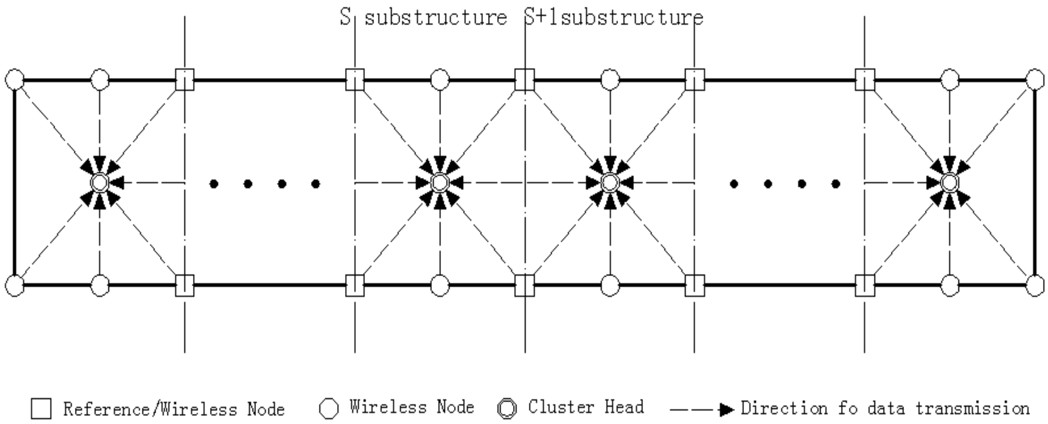

Fig. 5: Distributed computing strategy of modal identification with wireless sensing network

Figure 5, a large-size structure is divided into substructures. The distributed sensors in a substructure are grouped into a cluster. A cluster head is assigned to each cluster to collect the data from them.

Each sensing node in a cluster transfers its measured data to the cluster head where modal parameters of the substructure are identified based only the locally measured information in the cluster. Modal identification results of each substructure are the sent back to the central station where modal identification of the whole bridge can be constructed from the identified local modal parameters. Relevant experimental work is being conducted by the authors.

5 CONCLUSIONS

In this paper, a new type of wireless sensing network is proposed for monitoring large span bridges. The wireless network has two-level cluster-tree architecture. It provides not only a low power topology for long distance data transmission but also distributed computational capacity for parallel data processing in the network so as to reduce the amount of data transmission. Each cluster head in the network can be embedded with some computational algorithm, granting the wireless monitoring network with intelligent characteristics.

A distributed out-put only modal identification algorithm based on NExT and ERA is proposed for large size structure. Numerical example of distribute computing modal properties of three-span continuous beam illustrates efficiency of the proposed algorithm. The distributed modal identification algorithm can be incorporated into the new wireless sensing network for automated modal identification of large span bridges. Relevant work is being conducted by the authors.

5.1 Acknowledgements

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