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Experimental verification of decentralized approach for modal identification based on wireless smart sensor network

Xijun Ye[1,a], Tianfeng Zhu[2,b],Quansheng Yan[3,c], Weifeng Wang[4,d]

[1,2,3,4]School of Engineering and Transportation, South China University of Technology,

Guangzhou, 510641, China

[a]xijunye.scut@gmail.com, [b]scutztf@126.com, [c]cvqshyan@scut.edu.cn, [d]ctwfwang@scut.edu.cn

Keywords: Imote2; Wireless smart sensor network; Centralized; Decentralized topology; NExT- ERA; Modal identification; Normalization factor

Abstract: This paper provides an experimental verification of decentralized approach for modal test and analysis of a 30 meters long railway overpass bridge. 11 Imote2 smart sensor nodes were implemented on the WSSN. In order to compare the identification precision of different topologies, acceleration responses were obtained under centralized and 3 different decentralized topologies. Local modal parameters were estimated by NExT/ERA within each local group; true modes were then distinguished from spurious modes by EMAC and finite-element analysis. In order to estimate global mode shape, a least square method was used for calculating the normalization factor. Then the global mode shapes were determined by normalization factors and local mode shapes. The result demonstrates that the more overlapping nodes in each group, the more accurate the global mode shape will be; the decentralized approach is workable for modal test of large-scale bridge.

Introduction

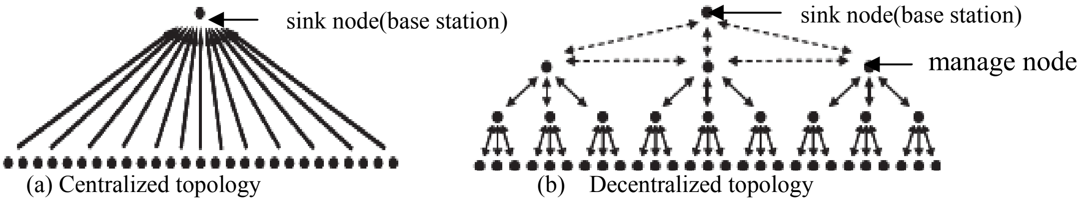
For modal testing of large span bridge using traditional wired sensor systems, a large array of sensors are needed to be deployed, which is costly, time-consuming, and difficult to deploy. For example, the health monitoring system of Tsing Ma Bridge in Hong Kong has 326 channels for monitoring, generating 65MB data per hour, cost more than 800 million dollars[1]. The total system cost, including installation, of the monitoring system on the Bill Emerson Memorial Bridge in Cape Girardeau, Missouri, USA is about $1.3M for 86 accelerometers. That makes the average installed cost more than $15,000 dollars for one sensor[2].

Recently, rapid advances in smart sensor and wireless communication technologies have made wireless smart sensor network widely used on the field of civil structure monitoring. In 1996, E.G. Straser and A.S. Kiremidjian[3] brought up a new idea of structure monitoring, replacing traditional wired monitoring system with wireless smart sensor network. Also they developed a wireless structural health monitoring system which can detect structure damage real-time. J.P. Lynch and K.H. Law [4] invented a wireless module monitoring system(Wireless Modular Monitoring Systems, WiMMS) for health monitoring of large-scale civil structures, which embedded signal processing algorithms in sensor nodes taking advantage of the processing ability of the smart sensors. In 2003, WiMMS was successfully deployed in the Alamosa Canyon Bridge[5] in New Mexico state for health monitoring. In 2008, B.F. Spencer deployed a wireless smart sensor network(WSSN) composed by Imote2 [6] in Jindo Bridge[7] , Korea, for health monitoring.

Compared with the traditional wired sensor systems, WSSN has obvious advantages, but limited by the ability of wireless communication. In 2006, Gao[8] proposed a distributed computing strategy (DCS) based on WSSN, small numbers of smart sensors are grouped to form different communities. The measured information is aggregated locally by a selected manage sensor within the sensor group, and only limited information is sent back to the base station to identify dynamic properties of the structure. In 2008, Zimmerman AT[9] tested a theater's stand based on DCS. Every two sensors were chosen as a group, one of them was overlapping sensor. Peakpicking(PP), FDD and RDT method were used to identify local modal parameters of each group, and then, to get global modal parameters. But the result showed that the global mode shape was not accurate enough, because only one overlapping sensor was used between every two groups, error was accumulated one by one. This paper provides an experimental verification of decentralized approach for modal testing and analysis on a 30 meters long railway overpass bridge based on WSSN. Different decentralized topologies were used for modal test to identify global modal parameters.

Decentralized network topology

For traditional wired sensor systems, centralized topology is used to obtain and process vibration responses. That is, original vibration response of each sensor node will be transmitted to a sink node(base station),Fig.1(a). But centralized topology is not workable for WSSN, because large number of data transmission will cause the network blocked, as while ,the battery of sensor nodes will be run out very soon. Therefore, Gao[8] proposed a decentralized network topology (Fig.1(b)), which is suitable for wireless sensor network.



(a) Centralized topology (b) Decentralized topology

Fig.1. Network topologies

The decentralized approach proposed by Gao[8] employs a coordinated computing strategy, which has the ability to reduce the amount of data and capture local spatial information. For decentralized approach, the network is divided into hierarchical communities, in which sensor nodes within each group communicate with each other in processing data; communication between groups is conducted through each community's manager node; then local modal parameters of each group will be transmitted to the base station.

Modal identification by NExT-ERA

Natural Excitation Technique(NExT). Theoretical justification of the NExT technique is that correlation functions (auto-and cross-correlation functions) calculated from measured output data (commonly acceleration measurements) can be expressed in terms of sum of decaying sinusoids which have the same damped natural frequency and damping ratio as the impulse response function of the original structural system. NExT is based on the two assumptions: 1) input excitations are a stationary random white noise and uncorrelated with the response which is also a weakly stationary random process; 2) the structural system is excited within linear elastic regime so that the principle of superposition is valid. Details on its theoretical aspects can be found in Reference [10].

To improve signals by reducing non-reproducible noise, ensemble averaging and windowing techniques are employed. Once impulse response of the system is obtained, ERA in the following section is used for modal identification.

Eigensystem Realization Algorithm(ERA). For $2N$ dimensional linear time-invariant system with m inputs and n outputs, its state equation and observe equation in discrete-time domain can be expressed as follows:

$$x(k+1) = Ax(k) + Bp(k) \tag{1}$$

$$y(k) = Cx(k) \tag{2}$$

where $X(k)$ is state variables, A, B, C are, respectively, the system matrix, control matrix and observation matrix.

The Hankel matrix $H(k)$ is:

$$H(k-1)=\begin{bmatrix} h(k) & h(k+1) & \cdots & h(k+s) \\ h(k+1) & h(k+2) & \cdots & h(k+s+1) \\ \vdots & \vdots & \ddots & \vdots \\ h(k+r) & h(k+r+1) & \cdots & h(k+r+s) \end{bmatrix} \tag{3}$$

where *h(k)* is the $(r+1)\times(s+1)$ impulse response vector of the *k-th* time step，and parameters ***r*** and ***s*** correspond to the number of columns and rows of the Hankel matrix．Theoretically，the rank of the Hankel matrix is constant，equivalent to the dimension of the system．For a system contaminated by noise，however，there exists rank deficiency．The rank of *H(k)* be constant only when parameters ***r*** and ***s*** are increased to an extent．

The ERA solution to the system realization problem uses singular value decomposition(SVD) when *k=1*. The SVD of the matrix *H(0)* ***l***eads to：

$$H(0)=U^T\Sigma V \tag{4}$$

where U and V are normalized orthogonal matrix; Σ is a diagonal matrix that the diagonal elements are singular values in decreasing order.

Retaining the first ***2N*** largest singular values of Σ and corresponding vectors of *U* and *V,* eq.(4) may be written as:

$$H(0)=U_{2N}^T\Sigma_{2N}V_{2N} \tag{5}$$

where $\Sigma_{2N}=diag\left(\sigma_1^2 \quad \sigma_2^2 \quad \cdots \quad \sigma_{2N}^2\right)$, $\sigma_1^2 \ge \sigma_2^2 \ge \cdots \ge \sigma_{2N}^2 > 0$.

Then the *2N* dimensional system realization is computed as follows:

$$A=\Sigma_{2N}^{-1/2}U_{2N}H(1)V_{2N}\Sigma_{2N}^{-1/2}, B=\Sigma_{2N}^{1/2}V_{2N}E_{ml}, C=E_{nl}^TU_{2N}^T\Sigma_{2N}^{1/2} \tag{6}$$

Implementing eigen value decomposition(EVD) to system matrix ***A***,

$$\Phi^{-1}A\Phi=\lambda \tag{7}$$

where $\begin{matrix}\lambda=diag\left[\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_{2N}\right] \\ \Phi=diag\left[\phi_1 \quad \phi_2 \quad \cdots \quad \phi_{2N}\right]\end{matrix}$,

according to the relationship of ***Laplace*** transform and ***Z*** transform,

$$s_i=\frac{\ln(\lambda_i)}{\Delta t} \tag{8}$$

modal parameters are obtained：

$$\omega_i=\sqrt{\left(\mathrm{Re}\,s_i\right)^2+\left(\mathrm{Im}\,s_i\right)^2} \qquad \text{frequency} \tag{10}$$

$$\xi_i=\frac{-\mathrm{Re}\,s_i}{\omega_i} \qquad \text{damping ratio} \tag{11}$$

$$C\Phi=E_{nl}^TU_{2N}^T\Sigma_{2N}^{1/2}\Phi \qquad \text{mode shape} \tag{12}$$

Details on the derivation can be referred to Reference[11].

Global modal parameter identification

Local modal parameter identification. For modal test using decentralized approach, sensors will be divided into *n* groups(Fig.2), and there are *r* sensor nodes overlapped between any groups. Data aggregation and processing are performed independently in each group. With the NExT method, Cross relation function of the responses can be used as input to the Eigensystem Realization Algorithm(ERA) to extract local modal parameters. EMAC (Extended modal amplitude coherence) is used as mode accuracy indicator to distinguish spurious modes.

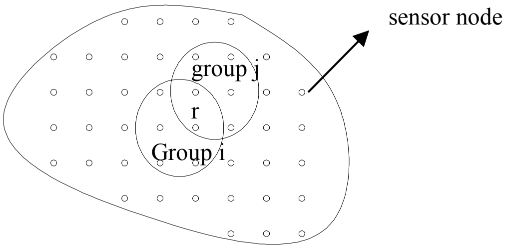


Fig.2 Network topology of wireless sensor network

Assembly of global modal parameter. Once the local information is collected centrally to the base station, the first task is to distinguish the true modes from the spurious modes. In this study, the true modes are selected based on the number of identified natural frequencies from the groups. The true modes should be identified in the majority groups, while the noise modes will randomly appear in the groups. Thus, if a specific natural frequency is identified in a substantial number of the groups, it is considered as a true mode. If ERA fails to find the true mode in certain groups, the cross spectrum is alternatively used to estimate the local mode shapes. Once the true modes are determined, the corresponding mode shapes can be combined together[12].

Theoretically, modal parameters of each group should be the same. However, due to the noise effect and computing errors, modal parameters of each group are not exactly the same. In this study, by averaging the modal parameters of all groups, the mean values(natural frequency and damping ration) are considered as the final result.

(1)Normalization factor

Consider the *m-th* mode, ϕ_i^m, ϕ_j^m are two sets of local mode shape from group ***i*** and ***j***, ϕ_i^m, ϕ_j^m can be expressed as :

$$\phi_i^m = \left\{1, \phi_{i,2}, \cdots, \phi_{i,p}, \phi_{i,1}^o, \cdots, \phi_{i,r}^o\right\}^T \tag{13}$$

$$\phi_j^m = \left\{1, \phi_{j,2}, \cdots, \phi_{j,p}, \phi_{j,1}^o, \cdots, \phi_{j,r}^o\right\}^T \tag{14}$$

where the superscript '*o*' denotes the overlapping nodes in the group ***i*** and ***j***; '***r***' is the number of overlapping nodes; *p* and *q* are the number of non-overlapping nodes in group ***i*** and ***j***.

To determine the *m-th* global mode shape, the local mode shapes of the overlapping nodes should be rescaled to have the same value as follows:

$$\left\{\phi_{i,1}^o, \cdots, \phi_{i,r}^o\right\}^T = R_{ij} \cdot \left\{\phi_{j,1}^o, \cdots, \phi_{j,r}^o\right\}^T \tag{15}$$

where R_{ij} is normalization factor.

By the least square method, figure out the best estimation of R_{ij}

$$\min(E) = \sum_{l=1}^{r}\left(R_{ij} \cdot \left\{\phi_{j,1}^o, \cdots, \phi_{j,r}^o\right\}^T - \left\{\phi_{i,1}^o, \cdots, \phi_{i,r}^o\right\}^T\right) \tag{16}$$

(2)Determine the global mode shape

With the normalization factor R_{ij}, local mode shape from group ***i*** and ***j*** can be assembled to global mode shape. But Limited by the number of sensors, usually more than two groups are needed for the modal test of large structure.

Supposed that sensor nodes were divided into *p* groups. There are at least one overlapping node between two adjacent groups. From group *2* to group *p*, the normalization factors are R_{12}, $R_{12}R_{23}$, $R_{12}R_{23}R_{34}$, $\cdots$, $R_{12}R_{23}R_{34}\cdots R_{(p-1)}$, which can be obtained by eq. (16).

Experimental verification

A simply-supported railway overpass bridge, which crosses the Guangzhou to Shenzhen railway, was tested in this study. The bridge is 30 meters long , 24 meters wide, Fig.3(a). In this paper, only vertical bending mode is tested to verify decentralized approach for modal identification. In order to get better modal parameters, 11 Imote2 smart sensors is employed on the deck, with 2.5 meter between each other , Fig.3(b).

(a) layout of the bridge (b) Imote2 sensor nodes

Fig.3 Field application

FEM analysis. To have a general idea of the dynamic properties of the bridge, a finite element model is modeled with Midas/Civil(Fig.5). The first three vertical bending modes were extracted, (Fig 6-8).

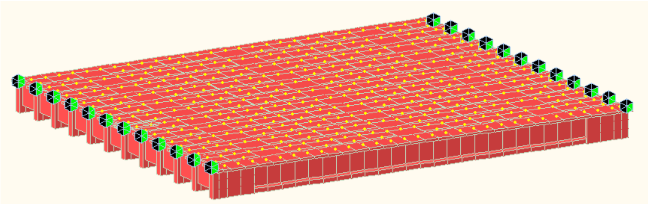


Fig.5 FE Model

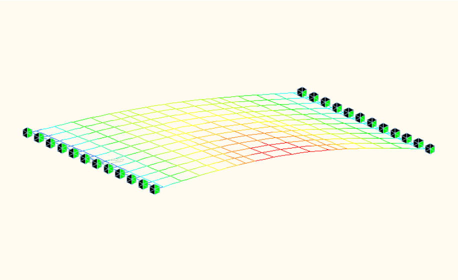


Fig.6 1st Bending Mode :F=3.95HZ

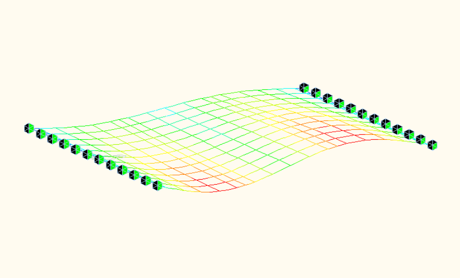


Fig.7 2nd Bending Mode: F=15.71HZ

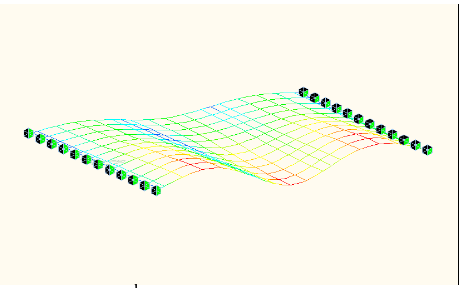
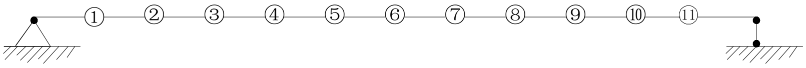
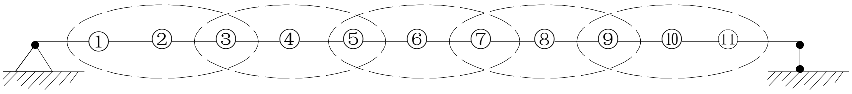


Fig.8 3rd Bending Mode :F=32.75HZ

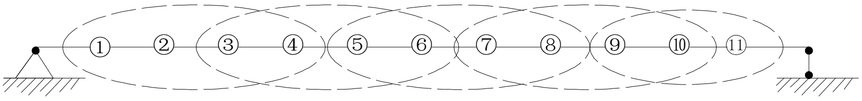
Network topology for modal test. Fig.9 shows the centralized topology and 3 different decentralized topologies. For decentralized approach, 3 different topologies are considered. Topology 1: one overlapping node; Topology 2: two overlapping nodes; Topology 3: three overlapping nodes.



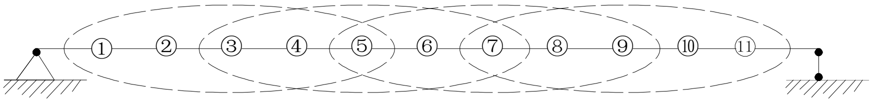
(a) Centralized



(b) Decentralized: Topology 1



(c) Decentralized: Topology 2

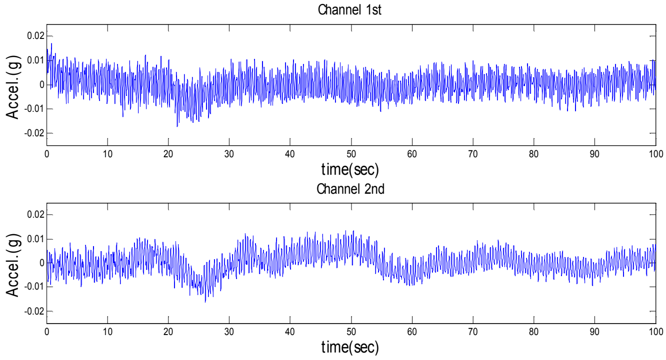


(d) Decentralized: Topology 3

Fig.9 Network topologies

modal analysis. (1). Local modal parameter identification

The sampling rate for data acquisition was set to be 100Hz, acceleration responses were acquired for 20mins in every topology. The data of topology 3 were chosen to be shown in this study. Acceleration responses and cross-relation function can be seen in the Fig.10-11.



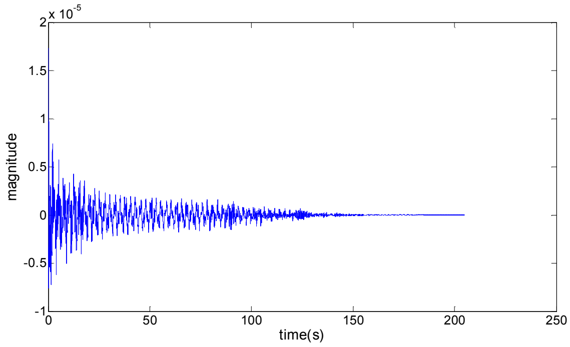
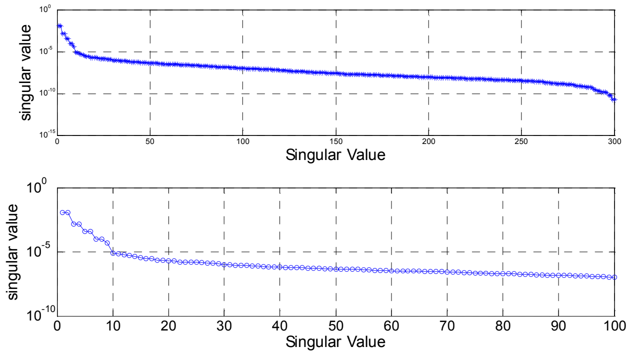


Fig.10 Acceleration responses

Fig.11 Cross-relation Function

In the ERA analysis, the Hankel matrix is set to have a size of 2048×2048. Applying SVD decomposition to the Hankel matrix, system order can be determined by the non-zero singular value, Fig.12. In this study, system order was chosen as 10. However, many spurious modes are included in the local mode shapes identified by the ERA analysis, EMAC was chosen as the mode accuracy indicator. Additionally, in this experimental testing, reference modal properties are obtained using peak-picking method, Fig.13.

From the EMAC value in Tab.1, we know the 3rd and 4th mode are spurious modes. This is the same with the power spectrum in Fig.13



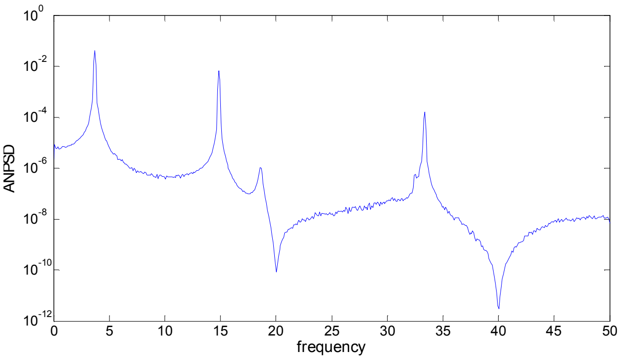


Fig.12 Singular value

Fig.13 Average power spectrum

Tab.1 Identification of natural frequency and damping ratios: Group2, Topology 3

mode	1	2	3	4	5
Fd (HZ)	3.713	14.872	18.673	33.461	33.592
Zeta (%)	0.94	0.61	0.01	3.78	0.50
EMAC (%)	0.989	0.972	0.302	0.219	0.986

(2) Global modal parameter identification

By averaging the local modal parameters of each group, the global natural frequencies and damping ratios can be obtained (As showed in Tab.2). The identified natural frequencies of different topologies are very close, but a little different from the FE model. So the FE model needs to be updated.

Tab.2 Natural frequency and damping rations from different topology

	Natural frequency(HZ)			Damping ratio （%）		
Topologies	mode			mode		
	1st	2nd	3rd	1st	2nd	3rd
FEM result	3.950	15.715	32.754	-	-	-
Centralized	3.753	14.530	33.640	1.60	3.43	1.68
Topology1	3.719	14.335	33.536	1.24	3.88	1.59
Topology2	3.721	14.472	33.598	1.18	4.02	1.77
Topology3	3.723	14.465	33.588	0.94	3.78	1.50

In topology 3, there are 4 groups, with 3 overlapping nodes between any groups. The first three local normalized mode shapes identified are listed in Tab.3. Tab.4 shows the normalization factor obtained by least square method, and the combined global mode shapes is showed in Fig.14-16.

Tab.3 The first 3 mode shapes from Topology 3

mode	Topology	Group number	Sensor node										
			1	2	3	4	5	6	7	8	9	10	11
1st mode	Centralized	-	1	1.93	2.73	3.35	3.73	3.86	3.73	3.35	2.73	1.93	1
	Tepology3	Group1	1	1.85	2.8	3.42	3.8						
		Group2			1	1.26	1.4	1.45	1.4				
		Group3					1	1.12	1.05	0.9	0.68		
		Group4							1	0.95	0.8	0.6	0.22
2nd mode	Centralized	-	1.00	1.732	2	1.732	1	0	-1	-1.732	-2	-1.73	-1
	Tepology3	Group1	1.00	1.75	2.10	1.80	0.98						
		Group2			1.00	0.93	0.58	0.00	-0.55				
		Group3					1.00	0.00	-0.89	-1.70	-2.08		
		Group4							1.00	1.80	2.05	1.79	1.10
3rd mode	Centralized	-	1.00	1.414	1	0	-1	-1.41	-1	0	1	1.414	1
	Tepology3	Group1	1.00	1.38	1.08	0.00	-1.12						
		Group2			1.00	0.00	-1.04	-1.45	-0.92				
		Group3					1.00	1.43	0.95	0.00	-1.09		
		Group4							1.00	0.00	-1.04	-1.46	-0.89

Tab.4 Normalization factors of Topology 3 from Mode 1st to 3rd

Number of topology	R_{ij}	1st mode	2nd mode	3rd mode
Topology3	R_{12}	2.733	2.011	1.078
	R_{23}	1.338	0.548	-1.010
	R_{34}	0.980	-1.003	1.000

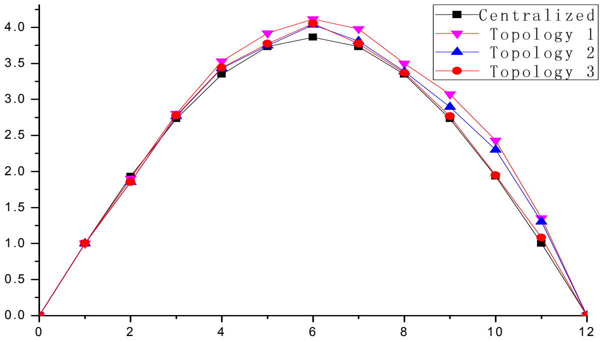


Fig.14 1st mode shape

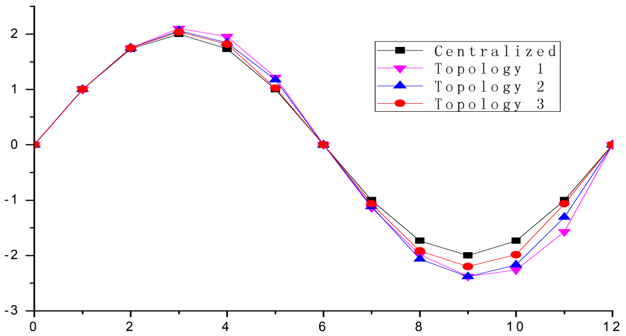


Fig.15 2nd mode shape

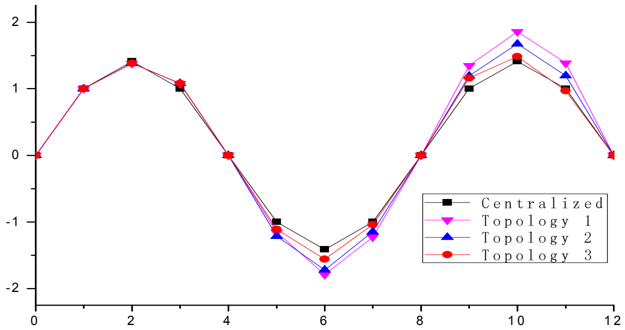


Fig.16 Global mode shapes of 3 topologies

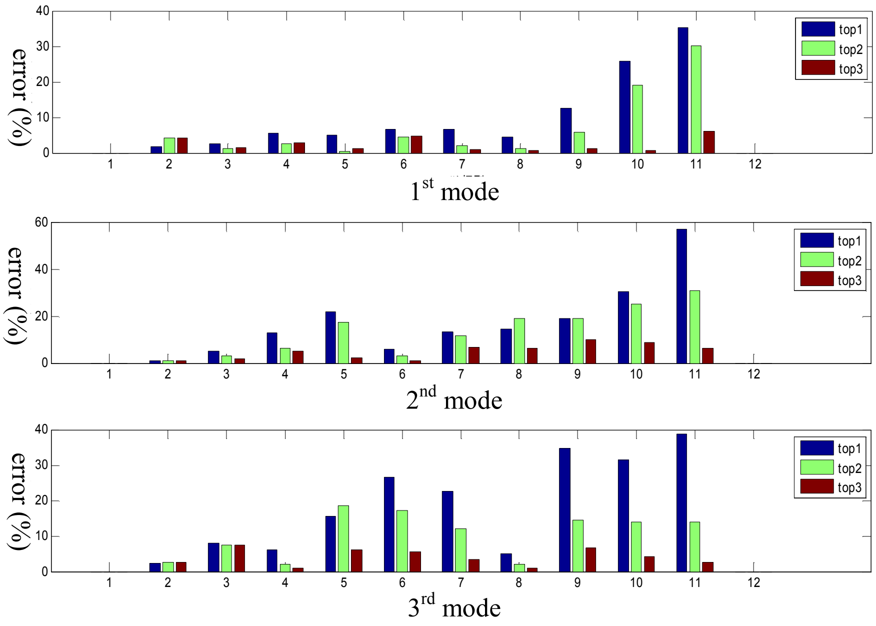


Fig.17 Identification accuracy of global mode shape in 3 topologies

From Fig.14-16, we can see that the global mode shapes are almost the same in different topologies from node 1 to node 5. But from node 6 to node 11, the error increase gradually, especially for Topology 1. In topology 1, there is only one overlapping node between any groups. So if the mode shape of either overlapping node is not accuracy enough, the combined global mode shape will cause larger errors.

When there are 2 or 3 overlapped nodes between either groups, Topology 2or Topology 3, the global mode shapes fit better with the centralized approach. Comparing to centralized approach, the global mode shape errors identified by decentralized approach are showed in Fig.17.

Conclusions

For modal test of large-scale structure, using wireless smart sensor is much more convenient. In this study, a simply supported bridge is tested. For the identified natural frequencies and damping ratios, the result are very close, but the global mode shapes are quite different from decentralized topologies with different overlapping nodes.

The maximum error of decentralized approach 1, 2 and 3 is 58.63%, 32.34% and 7.41%, compared to centralized approach. In Topology 3, there are 3 overlapped nodes in every group, that make the errors greatly decreased. The results of Topology 3 are very close to the result of centralized approach. So for cable-stayed bridge, suspension bridges and other large structures, in order to identify the global mode shapes more accurately, more than 3 overlapping nodes the proposed in each group.

Acknowledgements

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