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Technical Note

Remote Detection of Earthquake Induced Damage on Bridge Piers Using WSN Based on Dual Receiver and Phase Difference Measurement Technique

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ABSTRACT

In this study, a new technique for monitoring the structural health of bridge piers, from the point of view of earthquake induced damages, was introduced and was then simulated and evaluated by the use of a scaled model of a typical bridge. This system use the detection of phase difference between two synchronous receiver nodes connected through a wireless sensor network, and is based on using an array of inexpensive high-frequency oscillator circuits (4 GHz) as wireless transmitters through placing them in some important structural positions of the bridge piers, receiving and analyzing the signals sent by these transmitters by two synchronous receiver nodes. The proposed monitoring system measures the changes in phase difference between two synchronous receiver nodes before and after induced damages (displacement or deformation). It showed an accuracy of a tenth of a millimeter in the simulations, as well as a high reliability in monitoring the structural health of bridge because it provides a real-time report of status of each transmitter (activated, deactivated, damaged). The proposed system has a low price compared to other SHM methods and also has a much lower volume and complexity of data processing compared with similar techniques. This study did not have any field trial, but a complete simulation by the use of an array of six transmitters (TX) and two receivers (RX) was conducted for a scaled model with six piers. Mathematical derivation, geometrical principles, signal processing and simulation details was thoroughly examined.

Keywords:
Structural health monitoring; Earthquake induced damages; Phase difference detection technique; Bridge pier status monitoring; Dual synchronous receiver

1. Introduction

Maintaining the safety and service reliability of a large bridge over its relatively long life certainly needs obtaining continuous and reliable data about its structure, including damage caused by the temperature gradient, cracking, fatigue, corrosion of structures, the decrease of load capacity of the bridge, etc. that all should be carefully evaluated. Common measurements such as periodic visual inspections and controlled loading test are typical in this respect and their limitations and disadvantages have been thoroughly investigated. Some new technology utilized in structural health monitoring (SHM) [1-8] has recently attracted a lot of attention in the field of measurement and analysis of those mentioned factors especially by using wireless sensor networks.

In the present study, a SHM system that utilizes the wireless sensor networks (WSN) to detect displacement (or deformation) of bridge piers has been designed and evaluated with the help of a hypothetical bridge.

There are major drawbacks for the routine methods of SHM of the bridge structures, such as high price equipment, large number of requirements such as sensors, transducers, RF modules and wireless DAQs needed in each especial case for detecting and locating the occurrence of earthquake induced damages in bridge pier structures.

Whereupon all price increases, a large increase in the volume and complexity of data processing occurs. On the other hand, the diversity and breadth of the data collecting elements creates implicit problems such as increasing the network traffic, bandwidth limitations, power limitation and energy efficiency in wireless sensor networks [9-10]. The proposed method in this research has much lower final price and much less data-processing volume, in the same precision and resolution in detecting and locating the earthquake induced damages.

Authors of this paper claim that the proposed method has the ability to bypass the mentioned problems and limitations. The mathematical and geometrical principles and the method of signal processing and simulation will be explained in the second section of this article. In the third section, the results of simulation and its accuracy, the evaluation of capabilities of proposed SHM system in monitoring the structural health of bridge piers, and the advantages and disadvantages of this technique will be presented. The final section will summarize the issues discussed in this article.

2. Mathematical Derivation, Geometrical Principles, Method of Signal Processing and Simulation

This technique will detect the damages and deformation of bridge piers caused by strain using an array of transmitters (TX) installed on the piers of the bridge, sending the signals to two receivers. This system will in fact measure the changes in phase difference caused by displacement of transmitters by the use of two receivers, and will estimate and display the real-time status of the bridge piers with a tenth of millimeter accuracy. The System of paired synchronous receiver nodes will be installed in a location slightly away from the bridge and will demodulate the received signals independently with considering the correlation. The receivers R_0 and R_1 are also located in the vicinity of AOI (the location of array of transmitters) and might be affected by the vibrations and possible displacement caused by the earthquake and (just like transmitters placed on piers) might move from their original location considered in the system's training phase. In this paper, we assume that a set of special measures can be implemented to keep the predefined distance a (Eqs. (1) and (2)) between R_0 and R_1 constant. For example, a damping structure on which paired receivers will be mounted can be used to isolate and damp the seismic vibrations that might change the conditions considered in training phase.

As long as the initial value of a , that is defined in the training phase, is maintained, the proposed monitoring system can use the array of independent transmitters to calculate any displacement or deformation in the bridge piers caused by earthquake with verified reliability and an accuracy of a tenth of a millimeter. The simulation results, presented in section 3, will confirm this claim. By maintaining a, the structural health monitoring system proposed in this study is also capable of calculating the differential motion of each pair of modeled bridge piers. To further explain this point, we must mention that in proposed system transmitters located at AOI are analyzed and assessed separately, and the displacements and deformations of the pier corresponding to each transmitter are calculated and interpreted independent from the displacement of other transmitters or piers. Besides, given the independence of results regarding parameter δ (Eq. (9)) for each T_x, the proposed system ultimately will be able to easily calculate the differential motion.

We should state that even if an earthquake moves the paired receivers, assuming the proper functioning of mechanism implemented to maintain a (damper for example), receivers R_0 and R_1 will be displaced together at the same time, which will have no impact on the accuracy and evaluation of displacement of each transmitter and consequently the extent of damage to its corresponding pier. This claim is completely confirmed by our simulations. In fact, the fundamental important assumption here is that we are able to keep the distance a constant.

Much effort has been made to monitor the health and safety of bridge structures. It should be noted that since the communication is in RF range, the proper functioning of the system does not require a direct line of sight between the transmitters and paired receivers, and also no element in bridge pier, superstructure, or other objects within AOI can effectively block or refract the signals to hamper the proper functioning of the proposed monitoring system. This can be solved by using a multiplexed antenna which is installed over AOI space (at the highest point of the bridge and in direct sight of synchronous receivers) to send the signals of all transmitter, that completely fixes the above-mentioned problem.

The proposed method has an acceptable resistance against environmental noise and distortion because it measures the phase difference related to the transmitter (target) in the area of interest (AOI) and synchronized receiving nodes. AOI is the space between bridge piers and two receiver nodes installed in a location slightly away from the bridge structure. Array of T_X is planned to send data in a synchronized manner that repeatedly sends the string of (11111111) with a specific carrier frequency (4 GHz). The receiver nodes are installed in a location close to each other but slightly away from the bridge and demodulate signals independently but with a shared synchronous oscillator. The system can quickly detect displacement and deformation in an area of 250 m^2 using IEEE 802.11n network protocol and its related equipment. Incoming data can be sent to the secondary control centers for more processing. This technique is efficient in terms of resources because several arrays of transmitters and antennas can simultaneously share a data transmission circuit.In the following, first, a system with a single T_X will be assessed and the method of interpreting the phase shift to obtain a value for displacement will be investigated. Then, a system with an array of T_X will be assessed. Finally, the ambiguous state (path) will described and its mathematical equations will be assessed. The block diagram of the two receiver nodes will be presented, and the signals of transmitter and receiver will be described at each step (from transmission to detection). The 3-D simulations for obtaining the displacement and deformation of the bridge piers from the changes in phase difference will also be conducted.

2.1. Description of Wireless Transmitter - Receiver Model

Figure (1) shows an overview of the system of displaying the status of bridge piers. The AOI (Area of Interest) is the space encompassing the bridge structure and the space below the bridge deck, and an array of $T_X s$ (one T_X on each pier) is installed on the bridge. Each series of T_X was named T_1 to T_6 and was configured and programmed to send a predetermined data sequence to paired receiver nodes (training phase). These two synchronous receiver nodes (R_0 and R_1) were placed with a distance from AOI and bridge structure (in a short distance from each other represented by a).

2.2. Calculation of Displacement Based on One TX

Figure (2) shows a three-dimensional view of the model of the detecting system and monitoring damage and the deformation in bridge pier caused by the stress and strain. $T(x_0, y_0, z_0)$ is a set of $T_X s$

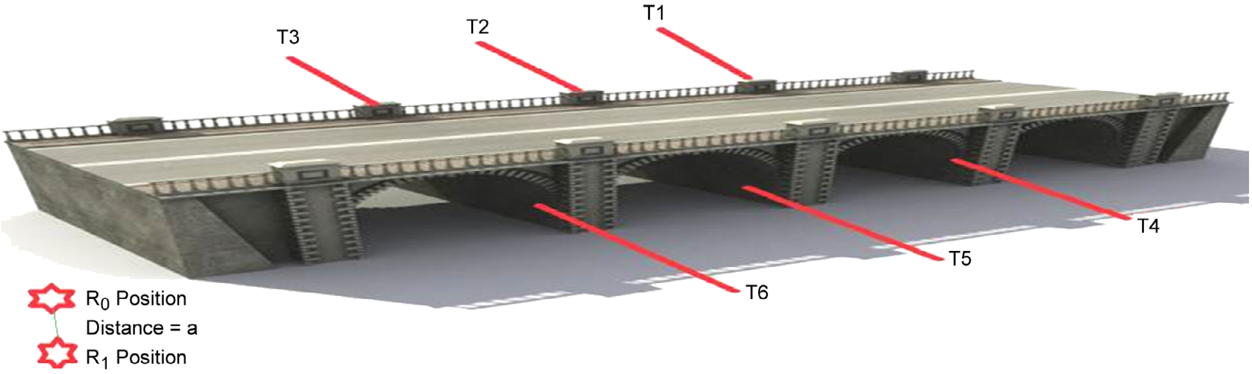
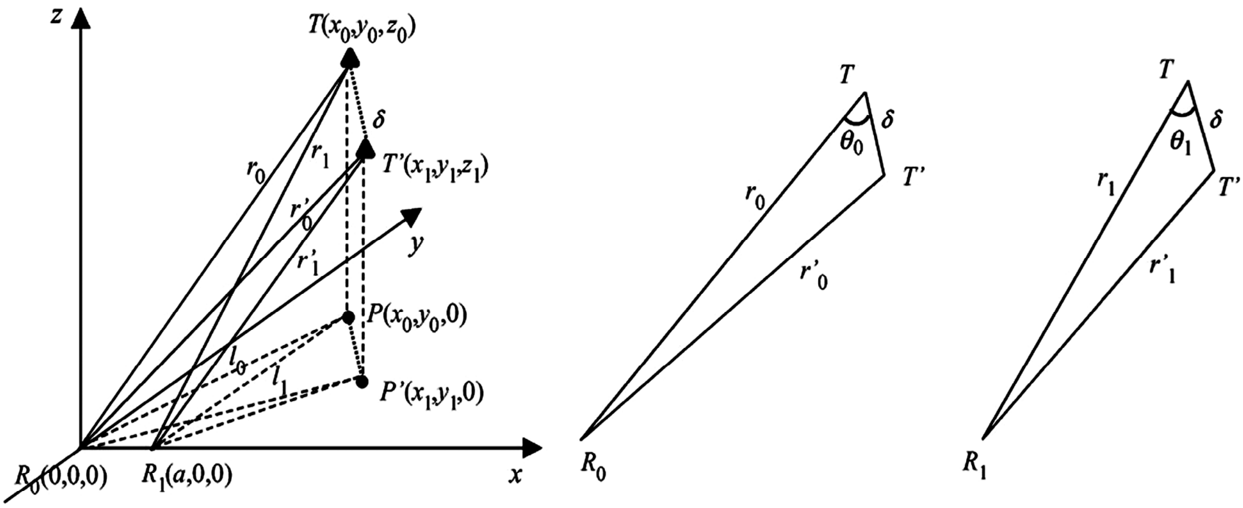


Figure 1. Arrangement of transmitters and the location of synchronous receivers on the sample bridge.



(a) (b) (c)

Figure 2. Status of node T and its state after damage (displacement or deformation of pier) which is called T′.

in AOI, and the first receiver node is called R_0, located at (0, 0, 0), and the second one (R_1) is located at (a, 0, 0). T' is the secondary location of the point T after displacement or deformation in the structure of bridge pier. δ is the amount of displacement or deformation and $p(x_0, y_0, 0)$ and $p'(x_1, y_1, 0)$ are the projections of T and T' on $X-Y$ plane. Deviation lines of (r_0, r_1) and (r'_0, r'_1) are the distances of R_0 and R_1 from T and T'. Therefore, we have:

$$r_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \tag{1}$$

$$r_1 = \sqrt{(x_0 - a)^2 + y_0^2 + z_0^2} \tag{2}$$

Angles of θ_0 and θ_1 are created by the lines of $R_1 - T$, $T - T'$, $R_0 - T$ and $T - T'$. During the initial installation of the system, the location of $T_X s$ and R_0 and R_1 should be measured so that parameters of a, Z_0, Y_0, and X_0 can be determined. Vector of the slope of bridge pier at point T can be estimated through the following method (the numerical method):

$$\vec{M} = (x_1 - x_0)\hat{x} + (y_1 - y_0)\hat{y} + (z_1 - z_0)\hat{z} \tag{3}$$

and the scalar value of pier slope is equal to:

$$M_{Th} = (z_1 - z_0) / \sqrt{(x_0 - x_0)^2 + (y_0 - y_0)^2} \tag{4}$$

In order to make the values of θ_0 and θ_1 known, considering this point that we do not know the position of $T'(X_1, Y_1, Z_1)$ after a damage has been occurred, the phase difference φ_D due to range difference $D = r_0 - r_1$ can be obtained. Without knowing the location of $T'(X_1, Y_1, Z_1)$, the phase difference φ'_D due to the range difference $D' = r'_0 - r'_1$ can namely be measured through two receivers.

Having two triangles of $T - T' - R_1$ and $T - T' - R_0$, the following equations can be obtained:

$$\begin{aligned} \vec{r}_0^{\,2} + \vec{\delta}^2 - 2\vec{r}_0.\vec{\delta}.\cos\theta_0 &= \vec{r}_0'^{\,2} \\ \vec{r}_1^{\,2} + \vec{\delta}^2 - 2\vec{r}_1.\vec{\delta}.\cos\theta_1 &= \vec{r}_1'^{\,2} \end{aligned} \tag{5}$$

Therefore:

$$\begin{aligned} r'_0 &\approx r_0 - \vec{\delta}.\cos\theta_0 \\ r'_1 &\approx r_1 - \vec{\delta}.\cos\theta_1 \end{aligned} \tag{6}$$

where θ_0, θ_1, r_0 and r_1 are parameters measured during the installation. Having obtained $D = r_0 - r_1$ and $D' = r'_0 - r'_1$ we will have:

$$\vec{\delta} = \frac{D - D'}{\cos\theta_0 - \cos\theta_1} \tag{7}$$

In Eq. (3), D' is unknown, but it can be calculated through measured φ'_D phase.

$$D' = \lambda . \varphi'_D / 360 \tag{8}$$

where λ is the wavelength of the carrier frequency. Notice that φ'_D is a wrapped value, namely, $0^\circ \le \varphi'_D \le 360^\circ$; therefore, the above equation provides only the fractional part of λ. For $\delta \le \lambda$, the value of $D - D'$ is fraction of λ as can be seen in examples shown in section 3. Hence, the integer part of D' can be derived from that of D. Given r_0 and $r_1, D = r_0 - r_1 = N_D\lambda + DD$ where $N_D = \mathrm{mod}(D,\lambda)$ and $DD = D - N_D\lambda$. The correct value of D' can then be computed as $D' = N_D\lambda + DD'$ alternatively, since $D - D'$ is a fraction of $\lambda, D - D' = DD - DD'$ and we have:

$$\delta = \frac{DD - DD'}{\cos\theta_0 - \cos\theta_1} \tag{9}$$

The mentioned formula and method can be easily expanded to the system with arrays of $T_X s$ [9].

3. Results and Discussion

3.1. Simulation Results Analysis

As mentioned in the previous section, a new technique based on the detection of phase difference between two synchronous receiver nodes was introduced and simulated for monitoring the damages (displacement and deformation) of bridge piers. Principles and methods of work were presented in detail in the previous section. With the help of the proposed method and implementing it in the form of simulation, the displacement of each transmitter installed on 6 piers of the hypothetical bridge can be measured with a tenth of a millimeter accuracy, and the calculated data can be used in various SHM applications of bridges, for example SHM of the piers, SHM of the bridge decks, SHM of the foundation part of the bridge and some proactive maintenance tasks on different bridges body parts or even other structures like pipelines or historical buildings. One of the major advantages of this method is to provide a professional visual representation of current condition of bridge piers and their condition after damages. After performing the simulation, results of the simulation are also gathered in Tables (1) to (3).

Table 1. Simulation results for 6 transmitters (part 1).

φ'_D (rad)	φ_D (rad)	τ_1 (s)	τ_0 (s)	r'_1 (m)	r'_0 (m)	r_1 (m)	r_0 (m)	*Tx*
250.6501	155.9104	5.5877e-08	5.7735e-08	17.0367	17.6139	16.7631	17.3205	T1
64.0094	64.0924	5.7927e-08	5.9722e-08	17.3787	17.917	17.3781	17.9165	T2
340.6818	340.774	5.7735e-08	5.9722e-08	17.3211	17.917	17.3205	17.9165	T3
206.7747	248.6303	5.9722e-08	6.1644e-08	18.2003	18.7683	17.9165	18.4932	T4
138.7033	147.8192	5.9722e-08	6.1824e-08	17.9725	18.6013	17.9165	18.5472	T5
10.7939	56.4564	6.1644e-08	6.3683e-08	18.7949	19.3972	18.4932	19.105	T6

Table 2. Simulation results for 6 transmitters (part 2).

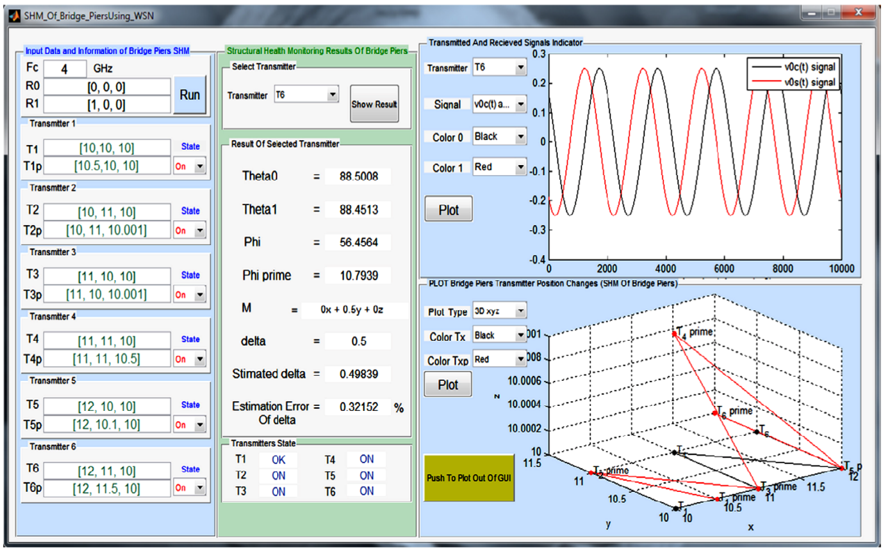
D' (m)	ΔD (m)	D (m)	θ_1 (Degree)	θ_0 (Degree)	M (No Unit)	m_t (No Unit)	m_a (No Unit)	*Tx*
0.57722	0.032481	0.55745	88.2915	88.3465	0.5x + 0y + 0z	-Inf	1.4524	T1
0.53834	0.013353	0.53833	89.9967	89.9968	0x + 0y + 0.001z	NaN	1.5305	T2
0.59598	0.070995	0.59596	89.9967	89.9968	0x + 0y + 0.001z	NaN	1.3813	T3
0.56808	0.051798	0.57677	88.4014	88.4513	0x + 0y + 0.5z	NaN	1.4487	T4
0.6289	0.030796	0.63076	89.6802	89.6911	0x + 0.1y + 0z	0	1.3255	T5
0.60225	0.011762	0.61173	88.4513	88.5008	0x + 0.5y + 0z	0	1.3841	T6

Table 3. Simulation results for 6 transmitters (part 3).

Estimation Error	$\delta_{estimated}$ (m)	δ_{real} (m)	$D - D'$ (m)	$\Delta D'$ (m)	*Tx*
0.14122%	0.50071	0.5	0.019765	0.052219	T1
4.3305%	0.00055669	0.001	9.6256e-06	0.013335	T2
4.8468%	0.00055153	0.001	1.0593e-05	0.070975	T3
0.33072%	0.49835	0.5	0.0086911	0.043078	T4
1.6607%	0.098339	0.1	0.0018676	0.028897	T5
0.32152%	0.49839	0.5	0.0094824	0.0022487	T6

3.2. Graphical User Interface Description

In this section, we will introduce a GUI designed for this application, and will assess the accuracy of the simulation results and will analyze proposed SHM system for a hypothetical bridge with 6 similar piers. GUI window related to the above inputs are shown in the following figure in which input data and calculated parameters (for example in relation with T_6) and received signals (for example $V_{0S}(t)$ and $V_{0C}(t)$) and also a 3D view of the results are displayed in Figure (3). Figure (4) shows this separate window designed for providing a closer



Fc 4 GHz
R0 [0, 0, 0]
R1 [1, 0, 0]

Transmitter 1
T1 [10,10, 10] State
T1p [10.5,10, 10] On

Transmitter 2
T2 [10, 11, 10] State
T2p [10, 11, 10.001] On

Transmitter 3
T3 [11, 10, 10] State
T3p [11, 10, 10.001] On

Transmitter 4
T4 [11, 11, 10] State
T4p [11, 11, 10.5] On

Transmitter 5
T5 [12, 10, 10] State
T5p [12, 10.1, 10] On

Transmitter 6
T6 [12, 11, 10] State
T6p [12, 11.5, 10] On

Transmitter T6

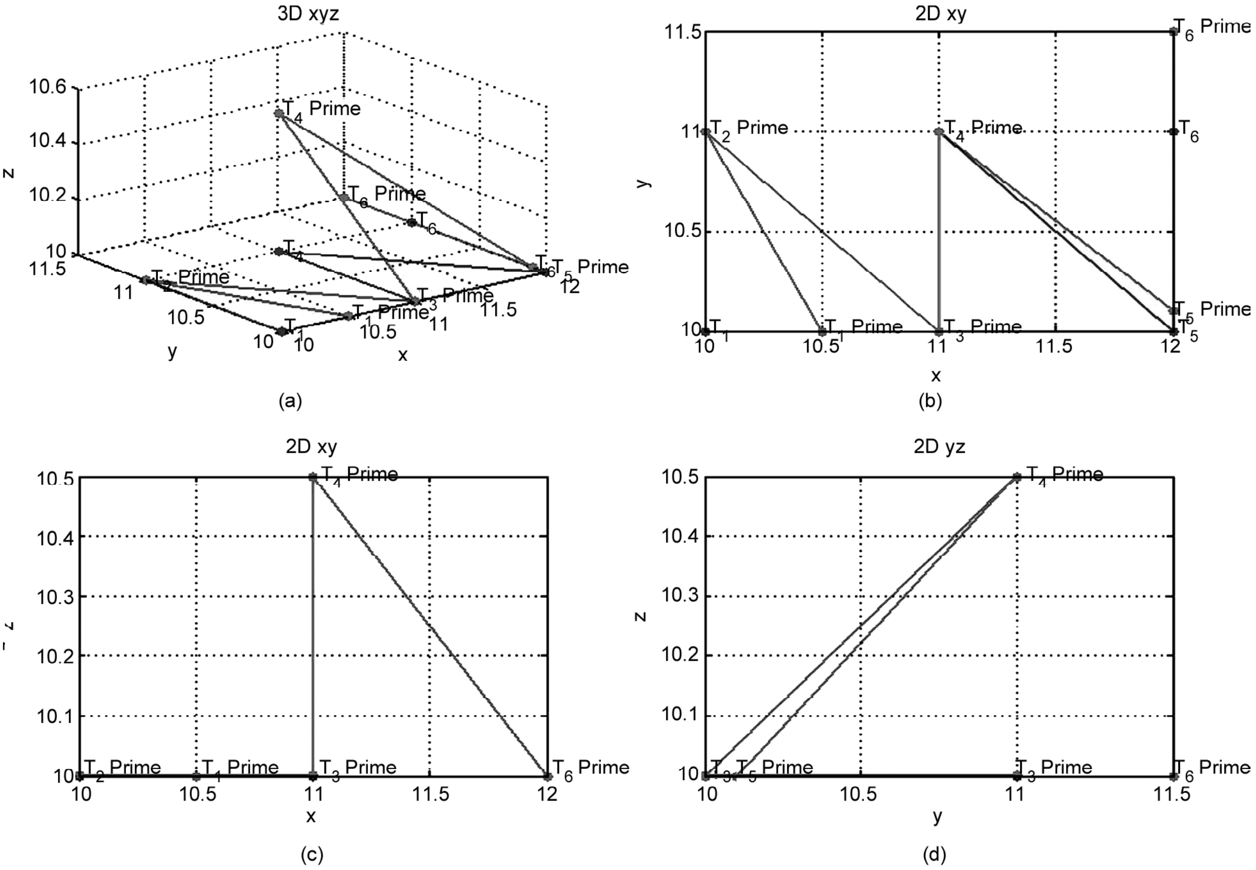
Theta0 = 88.5008
Theta1 = 88.4513
Phi = 56.4564
Phi prime = 10.7939
M = 0x + 0.5y + 0z
delta = 0.5
Stimated delta = 0.49839
Estimation Error Of delta = 0.32152 %

T1	OK	T4	ON
T2	ON	T5	ON
T3	ON	T6	ON

Transmitter T6
Signal v0c(t) a...
Color 0 Black
Color 1 Red

Plot Type 3D xyz
Color Tx Black
Color Txp Red

Figure 3. 3D graphical representation of the bridge piers in GUI before and after deformation, and also a view of step-by-step status of the signals in the receiver nodes.



(a)

(b)

(c)

(d)

Figure 4. Three perspectives displayed in a window separated from GUI to achieve better interpretation and understanding of the occurred events and the status of the bridge piers.

and more technical view of the simulation results:

With regard to the computational and graphical outcomes, the proposed method can be considered applicable in SHM systems of medium and large bridges. Calculation error for the value of δ was calculated in each run of the program (by comparing the results with the distance between the two points of T_X and T_X' obtained through the following formula) that was often a small and acceptable value.

4. Conclusion

In this study, a new method for monitoring the structural health of bridge piers was introduced, and then it was simulated and evaluated by the use of a scaled model of a typical bridge. This system uses the detection of phase difference between two synchronous receiver nodes connected through a wireless sensor network. The proposed system is based on using an array of inexpensive high-frequency oscillator circuits (4 GHz) as wireless transmitters through placing them in the important structural positions of the bridge piers, and then receiving and analyzing the signals sent by these transmitters by two synchronous receiver nodes. The proposed monitoring system measures the changes in phase difference between two synchronous receiver nodes before and after damage (displacement or deformation), and it showed an accuracy of a tenth of a millimeter in the simulations. It also showed a high reliability in monitoring the structural health of the bridge because of providing a real-time report on the status of each transmitter (activated, deactivated, and damaged). On the other hand, in the event of failure of any transmitter, proposed SHM system will announce its status but will continue its functions. Thus, this system will not be impaired by the damage or failure of one or more transmitters. The proposed technique and system had a much lower equipment cost compared with the other SHM methods and also had a lower volume and complexity of data processing compared with the similar techniques. This study did not have any field trial, but a complete simulation by the use of an array of six transmitters (T_X) and two receivers (R_X) was conducted for a scaled model with six piers, and mathematical and geometrical principles and signal processing and simulation details was thoroughly examined. Moreover, as previously stated, the high-frequency system and problem with line of sight as TX-RX must be in direct non-obscured path is not important in this method since the connection between T_X arrays and R_0 and R_1 receivers is made via RF(4GHz) link that does not need to be in direct contact via main transmission post. On the other hand, by using a multiplexed antenna that has been set on the top point of the bridge where it is in direct line of sight with receivers, T_X arrays and R_0 and R_1 will definitely be in direct non-obscured path. An example of a hypothetical damage to the bridge piers, along with the results and calculations of simulation by MATLAB was presented in order to assess the accuracy of the results and the reliability of the proposed SHM system. This System performs the separate calculations for each transmitter in the bridge piers, and in each run of the simulation it calculates and announces the damage estimation error through comparing the results with the formula of distance between two points in space. The proposed SHM system also has the ability to provide a 3D representation and to project it on Cartesian planes for more accurate visual assessment and monitoring. The presented discussions prove the claim of the researchers about the potential of this system in replacing current complex and expensive methods.

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