On-board data synchronization in wireless structural health monitoring systems based on phase locking

Kosmas Dragos¹, Michael Theiler¹, Filipe Magalhães², Carlos Moutinho² and Kay Smarsly¹

¹Chair of Computing in Civil Engineering
Bauhaus University Weimar, Coudraystraße 7, 99423 Weimar, Germany

CONSTRUCT–ViBest
Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

Abstract

Wireless sensor networks are prone to synchronization discrepancies, due to the lack of intrinsic global clock management from a centralized server. In wireless structural health monitoring (SHM) systems, synchronization discrepancies may lead to erroneous estimations of structural parameters of monitored structures. To avoid errors in the estimations of structural parameters, structural response data sets collected from a structure must be synchronized. Synchronization between structural response data sets can be achieved through offline processing. However, in wireless SHM systems offline processing requires wireless communication of entire structural response data sets, which has been proven detrimental to the power autonomy of wireless sensor nodes. This paper presents an embedded synchronization algorithm for wireless SHM systems. The embedded synchronization algorithm functions as a module added to embedded algorithms performing peak picking, which is part of operational modal analysis (OMA), for ensuring accurate outcomes. The embedded synchronization algorithm enables wireless SHM systems to synchronize structural response data sets on board using the embedded computing capabilities of wireless sensor nodes. The synchronization is achieved by imposing the expected relationship between the phase angles of Fourier spectra of acceleration response data sets at peaks corresponding to vibration modes. Time lags are autonomously estimated by the wireless sensor nodes through collaborative analysis of the phase angle relationship between acceleration response data sets collected by different sensor nodes. The embedded synchronization algorithm is implemented into a prototype wireless SHM system with embedded peak-picking algorithms and validated by laboratory tests and by ambient vibration tests on a pedestrian bridge.

Keywords: Synchronization; wireless sensor networks; embedded computing; structural health monitoring; operational modal analysis

1. Introduction

The logistics for installing structural health monitoring (SHM) systems, in terms of cabling, data acquisition units, and servers for storage and system management, have been posing non-negligible constraints in SHM applications [1]. Over the past three decades, wireless technologies have been introduced in SHM in an attempt to tackle these constraints [2, 3, 4, 5, 6, 7, 8]. Nonetheless, the most important shortcomings of wireless SHM systems stem from the features that constitute their very benefits over cable-based SHM systems [9, 10]. For example,
however cost-effective, eliminating wired connections adversely affects the reliability of data communication between wireless sensor nodes and servers [11, 12]. In this context, due to the absence of cables, wireless sensor nodes essentially operate as independent data acquisition units [13]. Consequently, the lack of centralized network management poses challenges to simultaneous sampling between different sensor nodes and may result in synchronization discrepancies [14].

Broadly speaking, synchronization is an issue of utmost importance in wireless sensor networks [15, 16]. Despite the state-of-the-art technologies regarding clock management adopted in modern wireless sensor networks, loss of synchronization between wireless sensor nodes may occur, for example, in sparse networks due to latency in wireless communication utilized to impose global clock management. Furthermore, potential malfunctions in clock operation, such as clock drifting, and non-simultaneous triggering of wireless sensor nodes may also result in synchronization discrepancies even in dense wireless sensor networks. Specifically in wireless SHM systems, synchronization discrepancies between structural response data sets collected by different sensor nodes may lead to erroneous estimates of structural parameters. For example, in operational modal analysis, which is widely applied in SHM [17, 18], data synchronization is a prerequisite for extracting accurate estimates of experimental mode shapes. Errors in experimental mode shapes may result from synchronization discrepancies affecting the phase angles at peaks in the Fourier amplitude spectra of acceleration response data sets corresponding to vibration modes (i.e. “modal peaks”) [19, 20]. Particularly in cases where high sampling rates are adopted to capture modal peaks at high frequencies, synchronization discrepancies may be detrimental to extracting accurate mode shapes of high-order vibration modes. To ensure accurate descriptions of structural behavior from wireless SHM systems, structural response data sets collected from different wireless sensor nodes must be synchronized.

Research efforts on data synchronization in wireless sensor networks and distributed systems are primarily found in the field of computer science. A review on synchronization challenges as well as on protocols and techniques adopted for synchronization in wireless sensor networks can be found in Dargie and Poellabauer (2011) [21]. One of the earliest efforts in synchronizing the clocks of distributed systems has been reported by Lamport (1978) [22]. Gusella and Zatti (1983) have presented a protocol for synchronizing distributed systems based on the exchange delays of timestamped messages transmitted among spatially distributed computers [23]. Christian (1989) has introduced a probabilistic approach towards clock synchronization in distributed systems [24]. In the field of wireless sensor networks, Elson and Estrin (2001) have devised a low-power post-facto synchronization scheme, where sensor nodes remain at sleep mode and are synchronized by recording the arrival time of a stimulus, which is then normalized to a reference pulse received from a third party node [25]. Elson et al. (2002) have proposed the “reference-broadcast synchronization” scheme, in which clock comparison between wireless sensor nodes is based on calculating the arrival time of non-timestamped beacon signals exchanged by the sensor nodes [26]. Moreover, Elson and Römer (2003) have recommended approaches for achieving sensor node synchronization based on state-of-the-art protocols [27]. A deterministic synchronization method for wireless sensor networks with minimal complexity has been presented by Sichitiu and Veerarittiphan (2003) [28]. Su and Akyildiz (2005) have reported a network-wide time-diffusion synchronization protocol [29]. Using a virtual consensus clock for network synchronization has been the focus of the protocol suggested by Maggs et al. (2012)
[30], and Chen et al. (2010) have introduced a feedback-based synchronization scheme in an attempt to accommodate clock drifting [31]. Liu et al. (2010) have suggested the use of Kalman filters towards self-correcting synchronization in wireless sensor networks [32]. Details on wireless sensor network synchronization schemes from a computer science perspective can be found in several reviews in literature [33, 34, 35, 36].

From a wireless SHM perspective, research efforts on synchronization have been focusing primarily on using GPS transceivers. For example, Bojko et al. (2009) have devised a wireless sensor node prototype using a GPS transceiver for achieving synchronization with the rest of the wireless sensor network [37]. Sazonov et al. (2010) have proposed a hierarchical architecture organizing wireless sensor nodes into clusters, while distinguishing between intra-cluster synchronization of sensor nodes achieved through beacon signals and inter-cluster synchronization performed via GPS [38]. Despite the attractive features of incorporating GPS into wireless sensor networks, the high power consumption of GPS receivers as well as the susceptibility of GPS operation to poor satellite coverage still pose constraints [39]. In a non-GPS-based synchronization implementation of a wireless sensor network for monitoring the Golden Gate Bridge at San Francisco, Kim et al. (2006) have used the flooding time synchronization protocol, introduced by Maróti et al. (2004) [40, 41]. Linderman et al. (2012) have reported on extending the flooding time synchronization protocol with features for estimating as well as for compensating for clock drifting in real-time sensing, achieving a constant synchronization error as low as 80 μs [42]. Other non-GPS network synchronization approaches are based on employing network protocols, such as the “time division multiple access” protocol and the “medium access control layer time protocol” [43, 44, 45, 46]. Moreover, Li et al. (2016) have proposed a strategy towards efficient time synchronization in wireless SHM systems by compensating for the effects of non-linear clock drifting [47]. Lei et al. (2004) have suggested using auto-regression-based algorithms for the offline synchronization of data from wireless SHM systems [48]. Finally, approaches towards clock synchronization schemes based on transmitting “beacon signals” sent by one sensor node used as a reference, according to which the rest of the sensor nodes adjust their internal clocks have been also reported [49, 50, 51].

The aforementioned approaches mainly achieve synchronization through implementing distributed networking. In this paper, an embedded synchronization algorithm is presented, enabling on-board synchronization of structural response data sets using embedded computing. The inherent processing capabilities of wireless sensor nodes, which have been utilized for on-board data processing in several research endeavors of the authors [52, 53, 54, 55, 56], are used for implementing and executing the embedded synchronization algorithm. The embedded synchronization algorithm essentially serves as a module added to embedded algorithms performing peak picking as part of frequency-domain operational modal analysis (OMA). Embedded OMA algorithms have been widely applied in wireless SHM, for example, in the work of Zimmerman et al. (2008) [57]. The synchronization algorithm builds on the work of Rosenblum et al. (2001), who have exploited the “phase-locking” concept towards detecting synchronous patterns in biomedical data [58]. Unlike existing OMA-based synchronization methods performed offline at the output stage [59, 60], the synchronization concept adopted herein enables removing time lags between structural response data at an intermediate OMA stage, rendering the proposed synchronization algorithm suitable for embedded processing in
wireless sensor nodes. For achieving data synchronization, the relationship between phase angles at modal peaks in the Fourier amplitude spectra of acceleration response data sets collected from different sensor nodes is utilized. Modal peaks are autonomously detected by the wireless sensor nodes, and the relationship between the phase angles is collaboratively analyzed by the sensor nodes. The embedded synchronization algorithm proposed in this study is implemented into a prototype wireless SHM system that is validated by laboratory tests on a shear frame structure and by field tests on a pedestrian overpass bridge.

In the second section of the paper, the embedded synchronization approach using acceleration response data sets is explained. The third section of the paper covers the implementation of the synchronization algorithm into a prototype wireless SHM system, and in the fourth section the validation tests are presented. The paper concludes with a summary and an outlook on future research.

2. An embedded algorithm for synchronizing acceleration response data sets

The embedded synchronization algorithm builds upon the relationships between phase angles of Fourier amplitude spectra of acceleration response data sets at modal peaks collected by different sensor nodes. The detailed mathematical background is given in Dragos et al. (2018) [61]. In this section, the fundamental principle of the embedded synchronization algorithm is described, followed by an outline of the algorithm steps.

2.1. Phase shift condition

Dynamic structural response is typically represented by the superposition of normal (real) vibration modes, which are essentially harmonic sinusoidal functions, each with different amplitude, frequency, and phase angle. It has been proven that harmonic sinusoidal functions describing the response of two locations \(i\) and \(j\) on the monitored structure at vibration mode \(m\) are either positively or negatively correlated [62]. Depending on the correlation \(\rho\) between the harmonic sinusoidal functions, the difference between phase angles \(\theta_i\) and \(\theta_j\) at vibration mode \(m\) can be expressed as

\[
\Delta \theta_m = \left| \theta_i - \theta_j \right|_m = \begin{cases} 0 & \text{for } \rho = 1 \\ \pi & \text{for } \rho = -1 \end{cases} \quad i, j, m \in \mathbb{N}
\]  

(1)

In practice, vibration modes can be estimated through selecting modal peaks in the Fourier amplitude spectrum of acceleration response data sets computed by the Fourier transform (FT), as shown in Eq. 2.

\[
F_\kappa(\omega) = \sum_{\kappa=0}^{N-1} f_n \cdot e^{-2\pi i n \frac{\omega}{N}} \quad \kappa \in [0, N] \quad N \in \mathbb{N} \quad \omega = \frac{\kappa}{(N \cdot \Delta t)}
\]  

(2)

The expression in Eq. 2 represents the discrete Fourier transform (DFT), which is the discretized version of FT, with \(F_\kappa\) being the complex \(\kappa\)-th point of the DFT of an \(N\)-point time series \(f\) at frequency \(\omega\). Time series \(f\) represents the acceleration response discretized at time step \(\Delta t\). From
the DFT, estimates of the phase angles at modal peaks can be obtained. Using the argument of complex value $F_κ$, the estimate $φ_o$ of the phase angle $θ$ at frequency $ωκ$ is calculated, as shown in Eq. 3.

$$φ_o(ωκ) = \arg(F_κ) = \arctan\left(\frac{\text{Im}(F_κ)}{\text{Re}(F_κ)}\right) \quad κ = ωκ \cdot Δt \cdot N$$

(3)

Drawing from the theory of signal processing, the estimate $τ$ of the time lag between acceleration response data sets $S_i$ and $S_j$ collected from locations $i$ and $j$ is given in Eq. 4.

$$τ = \frac{Δφ_o(ωκ) - Δθ_κ}{ωκ}, \quad Δφ_o(ωκ) = φ_o(ωκ)_{S_i} - φ_o(ωκ)_{S_j}$$

(4)

The term $Δθ_κ$ in Eq. 4 represents the expected phase difference between the acceleration response data sets at frequency $ωκ$ as given in Eq. 1, which is derived either from preliminary numerical analysis of the monitored structure or from engineering judgment. Due to the limited set of solutions of inverse trigonometric functions, the maximum value of $φ_o$ calculated from Eq. 3 is $2π$. By extension, the maximum time lag estimate that can be computed from Eq. 4 is $τ_{max} = 2π/ωκ = Tκ$. For time lags that exceed the period $Tκ$, the solution of Eq. 3 is expressed in a generalized form, as shown in Eq. 5.

$$φ(ωκ) = \arctan\left(\frac{\text{Im}(F_κ)}{\text{Re}(F_κ)}\right) = φ_o(ωκ) + kπ \quad k ∈ ℤ$$

(5)

Therefore, assuming that the acceleration response data set $S_j$ has a time lag $τ$ with set $S_i$, the expression for estimating the time lag is given in Eq. 6.

$$τ = \frac{φ(ωκ)_{S_j} - φ(ωκ)_{S_i} - Δθ_κ}{ωκ} = kπ + \frac{φ_o(ωκ)_{S_j} - φ_o(ωκ)_{S_i} - Δθ_κ}{ωκ}$$

(6)

$$⇔ τ = \frac{1}{2} Tκ \cdot k + \frac{φ_o(ωκ)_{S_j} - φ_o(ωκ)_{S_i} - Δθ_κ}{ωκ} \quad k ∈ ℤ$$

In the majority of civil engineering structures, the dynamic response is governed by one dominant mode, which is usually the fundamental mode represented by the left-most peak in the Fourier amplitude spectrum at the lowest frequency and designated by a frequency index set equal to $κ = 1$. Moreover, variable $k$ represents the factor of the half-period included into the overall time lag $τ$ and can, theoretically, assume any integer value. By assigning different integer values to $k_d$ for the dominant mode, a collection of “candidate” time lag estimates are obtained from Eq. 6. For positive values of $τ$, data set $S_j$ should be delayed with respect to data set $S_i$, while for negative values of $τ$, data set $S_j$ should be shifted forward. For selecting the final time lag estimate, an additional condition is necessary. To formulate this condition, the time lags at $p$ vibration modes other than the dominant mode are calculated for predefined values of $k$, and $k_d$
combinations of time lags are formulated based on minimizing the difference between the time lags at the $p$ vibration modes and the time lags at the dominant mode. The final time lag corresponds to the combination with the lowest standard deviation. As a result, Eq. 6 is extended into the “phase shift condition”, shown in Eq. 7.

$$\tau_{1,n} = \frac{1}{2} k_{j,n} T_i + \frac{\delta_s (\omega_i)_{j,i} - \delta_s (\omega_j)_{i,j} - \Delta \theta_i}{\omega_i}$$

$$v = [\tau_{2,n}, \tau_{3,n}, \ldots, \tau_{m,n}] \equiv D = \left( \frac{1}{m-1} \sum_{p=2}^{m} |\tau_{1,n} - \tau_{p,n}| \right) \rightarrow \min$$

$$\tau = [\tau_{1,n}, v] \equiv \sigma(\tau_n) \rightarrow \min \quad \tau_n \in [\tau_{1,n}, \tau_{m,n}]$$

The phase shift condition forms the basis of the embedded synchronization algorithm implemented into the prototype wireless SHM system. The steps of the algorithm are described in the next subsection.

### 2.2. Description of the embedded synchronization algorithm

To apply the phase shift condition given in Eq. 7 to acceleration response data sets from different sensor nodes, the expected phase differences at the fundamental mode as well as at $p$ higher vibration modes first need to be approximated. Once $\Delta \theta_1$ and $\Delta \theta_2, \ldots, \Delta \theta_p$ have been calculated, the algorithm can be applied using the same values for the expected phase differences in each analysis. Therefore, the embedded synchronization algorithm is composed of two stages, the “preliminary analysis” and the “main analysis”.

In the preliminary analysis, initial estimates of the expected structural dynamic properties of the monitored structure, typically the expected natural frequencies, are obtained, e.g. through numerical analysis. Next, preliminary acceleration response data sets are collected from the sensor nodes for extracting the experimental natural frequencies from the respective Fourier amplitude spectra. Then, the numerical analysis is updated to minimize the deviations between the expected natural frequencies and the experimental natural frequencies. From the updated numerical analysis, the expected mode shapes are derived, from which values $\Delta \theta_1$ and $\Delta \theta_2, \ldots, \Delta \theta_p$, representing the phase differences between acceleration response data sets $S_i$ and $S_j$, are calculated. The steps of the preliminary analysis are shown in Figure 1.
In the main analysis, new acceleration response data sets are collected and the corresponding experimental phase differences are calculated. Then, using the expected phase differences from the preliminary analysis, the time lag between structural response data sets $S_i$ and $S_j$ is calculated by applying the phase shift condition, given in Eq. 7, for predefined values of $k_d$. Finally, the experimental mode shapes are corrected according to the synchronized acceleration response data sets. The steps of the main analysis are illustrated in Figure 2.
3. A wireless SHM system with on-board synchronization capabilities

In this section, the prototype wireless SHM system designed for implementing the embedded synchronization algorithm is presented. First, the operation of the SHM system is described. Next, the software embedded into the wireless sensor nodes for performing on-board data synchronization is illuminated.

3.1. System operation

The prototype wireless SHM system consists of wireless sensor nodes, a host computer, and a gateway node. The gateway node serves as a wireless communication interface between the sensor nodes and a host computer, the wireless communication being achieved through peer-to-peer wireless links.

The first task of the host computer is to initialize the SHM system and to send the network information as well as the analysis parameters to the wireless sensor nodes. Furthermore, in the preliminary analysis, the host computer receives the experimental natural frequencies from the sensor nodes. Subsequently, upon updating the expected natural frequencies, the expected phase differences are calculated and sent to the sensor nodes. Finally, once the wireless sensor nodes have completed the synchronization, the host computer receives the complex Fourier values at the modal peaks, which are used for applying frequency domain decomposition to extract the experimental mode shapes [63].

The wireless sensor nodes are equipped with embedded OMA algorithms that perform peak picking on board. The synchronization is performed after the peak picking stage is complete in a collaborative manner. First, upon receiving the network information and the analysis parameters from the host computer, the sensor nodes start sampling a predefined amount of acceleration response data. Next, in the preliminary analysis, the sensor nodes transform their own acceleration response data sets into the frequency domain via an embedded FFT algorithm followed by the peak picking in the Fourier amplitude spectra. The experimental natural frequencies of the modal peaks detected from peak picking are sent to the host computer. Then, the sensor nodes receive the expected phase differences from the host computer to apply the phase shift condition. In the main analysis, the sensor nodes collect new acceleration response data sets and calculate the corresponding Fourier amplitude spectra. One sensor node, which is a priori designated as “reference” node, sends its own phase angles to the rest of the sensor nodes, which, in turn, use their own phase angles and the phase angles of the reference node to apply the phase shift condition. Next, following the completion of synchronization, the sensor nodes send a confirmation message to the reference node, and all sensor nodes start sending the Fourier values at modal peaks to the host computer. The system operation is illustrated in Figure 3.
3.2. Software description

For performing on-board data synchronization, the embedded synchronization algorithm is designed as a software module that functions as an add-on to the embedded peak-picking (PP) algorithms. The embedded synchronization algorithm and the embedded PP algorithms are bundled into the same software. The software consists of two applications, a “host application”, running on the host computer, and an “on-board application”, running on each wireless sensor node. The software is implemented in Java programming language exploiting the object-orientation paradigm. Specifically, the embedded synchronization algorithm is implemented in a Java class, which cooperates with classes responsible for PP for executing the synchronization-related tasks.
The host application contains Java classes that handle the tasks of the host computer, which are organized into two packages: the “appmanager” package, which is responsible for coordinating the application tasks, and the “oma” package, which is designed for applying the frequency domain decomposition. The application is started by the PPHostApp class in the appmanager package, which also contains the following classes: NetworkInfoReader, NetworkManager, AnalysisManager, and BaseTransceiver. The PPHostApp class is also responsible for the network setup and the analysis management. The NetworkInfoReader class reads predefined information on the wireless communication links according to the communication protocol selected. For defining network information, such as IEEE addresses of the sensor nodes for communication, the NetworkManager class is devised. The AnalysisManager class is used to enter the analysis parameters, such as sampling rate, length of the acceleration response data sets and measuring direction, as well as the modes and the expected phase differences for synchronization. The BaseTransceiver class handles incoming and outgoing communication between the host computer and the sensor nodes.

The oma package contains two classes: ModalIdentification and Complex. The ModalIdentification class extracts experimental mode shapes by performing frequency domain decomposition, while the Complex class enables mathematical operations with complex numbers. For extracting mode shapes, several classes from the JAMA library, an open-source library provided by MathWorks and by the National Institute of Standards and Technology for performing matrix operations, are employed [64]. A UML class diagram of the host application is shown in Figure 4.

The on-board application running on each wireless sensor node, illustrated in Figure 5, comprises two packages, the appmanager package and the fourieranalysis package. The appmanager package manages the analysis steps, including the synchronization, and it contains the following classes: PPOnBoardApp, Analysis, Sampling, Synchronizer, and Transceiver. The PPOnBoardApp class manages the launching of the applications, the retrieval of analysis results, and the communication of the results to the host computer. The class Transceiver establishes wireless connections between a wireless sensor node and the host computer as well as between a wireless sensor node and the reference node. In addition, the wireless sensor nodes use the Transceiver class for receiving the information required for performing the peak picking analysis and for sending the peak picking results (i.e. modal peaks) to the host computer. The Analysis class is responsible for conducting both the preliminary analysis and the main analysis. The collection of acceleration response data is managed by the Sampling class. The embedded synchronization algorithm is implemented in the Synchronizer class, which cooperates with three classes: i) the Analysis class for retrieving the modal information (i.e. modes and expected phase differences) necessary for applying the phase shift condition, ii) the classes from the fourieranalysis package for calculating experimental phase angles, and iii) the Transceiver class for communicating with other wireless sensor nodes. Moreover, in the Synchronizer class, a family of time lags $\tau$ is calculated by applying Eq. 7 via methods “getForwardTimeLags” and “getBackwardTimeLags”.
The final time lag is obtained after imposing the condition of Eq. 7 for \( p \) higher modes, which is implemented into the “getFinalTimeLag” method.

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**Figure 4. UML class diagram of the host application**

The fourieranalysis package, designed to detect modal peaks, has five classes: PeakPicking, FFT, Complex, FourierSpectrum, and Average. The PeakPicking class is used to detect candidate peaks on the Fourier amplitude spectrum, and the FFT class applies the fast Fourier transform (FFT) to the acceleration response data sets. The class FourierSpectrum is responsible for computing the Fourier amplitude spectrum and the Fourier phase spectrum, along with the corresponding Fourier complex-valued series derived from the FFT class. Classes Average and Complex are used for averaging of Fourier spectra and for facilitating mathematical operations with complex numbers, respectively.
The prototype wireless SHM system is validated through laboratory and field tests, which are described in the next section.

### 4. Validation of the embedded synchronization algorithm

Two series of validation tests are devised for showcasing the ability of the prototype wireless SHM system to synchronize acceleration response data sets. First, to verify the operability of the SHM system, laboratory tests are performed under controlled input excitation. Second, to validate the applicability of the SHM system when the monitored structure is subjected to unknown excitations, field tests are conducted on a pedestrian overpass bridge under operational conditions.
4.1. Laboratory tests

The purpose of the laboratory tests is to confirm that the wireless SHM system operates as expected under controlled excitation and with minimal interference from external measurement factors, such as ambient noise. In the following subsections, the structure used for the laboratory tests is presented, followed by a description and discussion of the tests.

4.1.1. Laboratory test structure

The test structure is a three-story shear frame structure shown in Figure 6. Each story, 170 mm high, is composed of a 150 mm × 150 mm × 10 mm (width × length × thickness) steel plate resting on 4 aluminum columns with dimensions 15 mm × 2 mm (width × thickness). To increase the stiffness along the “weak” (i.e. more flexible) direction of the columns, two L13×13×2-profile beams are fixed to the column heads spanning the width of the plates. At the column bases, the structure is fixed to a steel plate, which facilitates the structure being mounted on a shake table. A study of the structural dynamic properties of the shear frame structure can be found in Magalhães et al. (2004) [65].

Figure 6. Shear frame structure used for the laboratory tests


4.1.2. Numerical modeling

Prior to conducting the laboratory tests, information from numerical modeling of the shear frame structure is used to extract the expected mode shapes for applying the phase shift condition. Particularly, the results from the numerical modeling of the shear frame structure performed by Magalhães (2004) [66] are retrieved. The numerical modeling assumptions include the fully-fixed column-to-plate connections, the full rigidity of the steel plates, and the lumping of structural masses at the story levels by neglecting the masses of the columns. In addition, the connections at the base level of the columns are considered clamped. The modulus of elasticity of aluminum is assumed equal to $75 \cdot 10^6$ kN/m$^3$ and the mass density of steel is taken equal to 7850 kg/m$^3$. The aforementioned properties correspond to a total mass per story equal to 1.766 kg and a stiffness per story equal to 7.328 kN/m. As a result, modal analysis yields the eigenfrequencies and mode shapes shown in Figure 7.

![Mode shapes](image)

Figure 7. Mode shapes from numerical analysis of the laboratory structure

The mode shapes from Figure 7 will be used as expected mode shapes to be compared with the mode shapes extracted from the laboratory tests. Furthermore, the expected phase differences necessary for applying the phase shift condition will be obtained based on the expected mode shapes.

4.1.3. Experimental setup

For the validation tests, the Java-programmable “Oracle Sun SPOT” sensor nodes are employed [67]. Each sensor node has dimensions 41 mm × 70 mm × 23 mm (length × width × height) and weighs 54 g. The main board of each sensor node is equipped with a 400 MHz ARM main processor, 1 MB RAM, and 8 MB flash memory. For wireless communication, an IEEE 802.15.4-compliant radio transceiver is installed in the main board. Each sensor node features an application board with an 8-bit resolution digital output accelerometer and a temperature sensor. The digital output accelerometer, type MMA7455L, measures at a selectable range between ±2 g and ±8 g and at a rate up to 250 Hz.
The laboratory shear frame structure is mounted on a shake table and one sensor node is placed at the center of each story, as shown in Figure 8. The base plate of the shear frame structure is fully fixed to the shake table through bolts. For the sake of simplicity, the tests are only conducted in the $x$ direction; hence, the sensor nodes are oriented to measure along the excitation direction.

![Figure 8. Experimental setup of the laboratory shake table tests](image)

4.1.4. Description of the laboratory tests and discussion of the results

First, the host computer automatically initializes the SHM system and sends the network information along with the analysis parameters to the wireless sensor nodes. In accordance to the phase shift condition given in Eq. 7, for calculating the candidate time lags, several values for integer $k_d$ are considered with minimum $k_d = 1$ and maximum $k_d = 4$. The number of mode shapes considered is $p = 3$ (Eq. 8). Upon receiving the network information and the analysis parameters, the sensor nodes measure the average ambient noise (acceleration at rest) for a limited period of time, which in these tests is set to $t_{cal} = 1500$ ms, specified based on experience from previous tests with the same sensor nodes. Then, the structure is subjected to broadband white noise excitation and the sensor nodes start sampling acceleration response data once a predefined acceleration threshold is exceeded. The length of the acceleration response data sets is set to $N = 4096$, and the sampling rate is set to $f_s = 125$ Hz. The excitation direction is aligned with the weak side of the column cross section; therefore, the Fourier amplitudes at modal peaks are expected to be maximum.

The completion of sampling is followed by the peak picking as part of the preliminary analysis. Once the modal peaks are received by the host computer, the expected phase differences, calculated through modal analysis of the numerical model, are sent to the sensor nodes for applying the embedded synchronization algorithm. The sensor node of the first story is designated as reference node in these tests. After synchronizing the acceleration response data sets and prior to sending the Fourier values to the host computer, the sensor nodes perform on-
board averaging of the acceleration response data sets using a window of 2048 points to enhance the accuracy of the Fourier values at modal peaks by minimizing the noise effects. The sensor nodes send the Fourier values at modal peaks to the host computer, where the experimental mode shapes are extracted.

A total of two laboratory tests are conducted by varying the acceleration threshold for sampling; in test 1, the threshold is set equal to $a_t = 0.25$ g and in test 2 it is set equal to $a_t = 0.35$ g. The purpose of varying the acceleration threshold is to induce diverse time lags between acceleration response data sets in each test, caused by the non-simultaneous triggering of the sensor nodes. To highlight the synchronization capabilities of the proposed embedded synchronization algorithm, both tests are repeated without applying synchronization and the experimental mode shapes from the non-synchronized acceleration response data sets are compared to the experimental mode shapes from the synchronized acceleration response data sets. The mode shapes from test 2 with and without applying the embedded synchronization algorithm are exemplarily plotted in Figure 9.

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<tr>
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<th>Mode 1 ($f_1 = 4.46$ Hz)</th>
<th>Mode 2 ($f_2 = 12.77$ Hz)</th>
<th>Mode 3 ($f_3 = 18.02$ Hz)</th>
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<td>Figure 9. Experimental mode shapes from the laboratory shake table tests</td>
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As can be seen from Figure 9, the sensor nodes in the prototype wireless SHM system can successfully synchronize the acceleration response data sets resulting in correct experimental mode shapes. Minor discrepancies between the “synchronized” experimental mode shapes and the mode shapes from numerical analysis are attributed to modeling uncertainties. Slightly larger discrepancies are observed in the third vibration mode, which are attributed to the mode not being adequately excited.

4.2. Field tests

For validating the embedded synchronization algorithm under operational conditions with no control over the excitation, field tests are conducted on a pedestrian overpass bridge. First, the pedestrian bridge is described. Next, the experimental instrumentation is illustrated, the field tests are presented, and the results are discussed.

4.2.1. Description of the pedestrian overpass bridge

The pedestrian overpass bridge is located in Matosinhos, Portugal. As shown in Figure 10, the bridge connects two popular sites of increased tourist traffic, the “Parque da Cidade” (Porto City Park) and the “Edifício Transparente” (Transparent Building), along the coastline of Matosinhos. Hence, the bridge is frequently subjected to relatively intense pedestrian traffic.

![Figure 10. View of the pedestrian overpass bridge](image)

As illustrated in Figure 11, the bridge has a two-span structural system, each span having a length of 30 m, a width of 3.5 m, and an inclination angle with respect to the horizontal plane of 6°. In the longitudinal direction, the deck rests on two steel girders, and in the transverse direction, the bridge is supported by a system of steel x-braces. The deck, whose finishing is made of timber, abuts at one end the Edificio Transparente building and at the other end a slope of the Parque da Cidade, both connections considered simply supported. At the middle of the bridge length, the deck rests on a reinforced concrete pier; the pier-to-deck connection is considered hinged.
4.2.2. Experimental setups

The sensor nodes used for the field tests are the same as the sensor nodes used for the laboratory tests (Oracle SunSPOT). Given that the field tests serve merely as validation for the applicability of the embedded synchronization algorithm, a full-scale instrumentation would fall beyond proof of concept. Hence, the instrumentation is limited to four wireless sensor nodes, one gateway node, and one host computer. Past tests on the pedestrian bridge have demonstrated that the dynamic behavior of the bridge is characterized by a combination of closely-spaced vertical bending and torsional vibration modes [68]. To efficiently capture the vertical bending as well as the torsional modes, two sensor nodes are attached to the web of each girder section. Ideally, the field tests would be performed in one experimental setup by placing two wireless sensor nodes at the middle of each span, thus allowing capturing all dominant vibration modes. However, this experimental setup would not be possible due to distance limitations for ensuring reliable wireless communication. As an alternative, two experimental setups are selected, one with all sensor nodes placed at one span and one with two sensor nodes placed at each span, but close to the pier, as shown in Figure 11. In both setups, the sensor nodes, labeled A, B, C and D, are oriented to measure the vertical response of the girders ($z_A$, $z_B$, $z_C$, and $z_D$). The aim of setup 1 is to describe the mode shapes of each individual span, while setup 2 is expected to illustrate the symmetry or anti-symmetry of the mode shapes between the two spans.

Figure 11. Experimental setups for the field tests on the pedestrian bridge
4.2.3. Description of the field tests and discussion of the results

The tests are conducted under operational conditions, which includes pedestrian traffic (mainly from the crew conducting the tests), wind, and vehicular traffic under the bridge. The excitation is assumed to be broadband, thus falling into the category of ambient vibration testing. The phase shift condition parameters are set equal to \( k_d = 1 \ldots 4 \) and \( p = 4 \). The excitation threshold is set equal to \( a_t = 0.13 \) g, given the lower expected oscillation amplitudes of the pedestrian bridge as compared to the laboratory shear frame structure. The number of data points collected by the sensor nodes in each acceleration response data set is set to \( N = 4096 \). For the preliminary analysis, the expected phase differences are obtained from the experimental mode shapes presented in Moutinho et al. (2015) [68], which are shown in Figure 12. A total of four experimental mode shapes are extracted from the two setups, which are illustrated in Figures 13-16.

![Figure 12. Experimental mode shapes of the pedestrian bridge (Moutinho et al., 2015)](image-url)
Figure 13. First experimental mode shape of the pedestrian bridge

Mode 1 ($f_1 = 1.95$ Hz)

<table>
<thead>
<tr>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_A = 1.15$</td>
<td>$z_A = -1.71$</td>
</tr>
<tr>
<td>$z_B = 0.79$</td>
<td>$z_B = -1.46$</td>
</tr>
<tr>
<td>$z_C = 1.68$</td>
<td>$z_C = 2.03$</td>
</tr>
<tr>
<td>$z_D = 1.00$</td>
<td>$z_D = 1.00$</td>
</tr>
</tbody>
</table>

Figure 14. Second experimental mode shape of the pedestrian bridge

Mode 2 ($f_2 = 2.05$ Hz)

<table>
<thead>
<tr>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_A = -1.52$</td>
<td>$z_A = 3.76$</td>
</tr>
<tr>
<td>$z_B = 0.58$</td>
<td>$z_B = -1.42$</td>
</tr>
<tr>
<td>$z_C = -2.17$</td>
<td>$z_C = -0.70$</td>
</tr>
<tr>
<td>$z_D = 1.00$</td>
<td>$z_D = 1.00$</td>
</tr>
</tbody>
</table>

Figure 15. Third experimental mode shape of the pedestrian bridge

Mode 3 ($f_3 = 3.27$ Hz)

<table>
<thead>
<tr>
<th>Setup 1</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_A = 0.36$</td>
<td>$z_A = 0.88$</td>
</tr>
<tr>
<td>$z_B = 0.65$</td>
<td>$z_B = 0.53$</td>
</tr>
<tr>
<td>$z_C = 0.85$</td>
<td>$z_C = 0.74$</td>
</tr>
<tr>
<td>$z_D = 1.00$</td>
<td>$z_D = 1.00$</td>
</tr>
</tbody>
</table>
The experimental mode shapes appear to be in good agreement with the mode shapes reported in the previous study (Figure 12). Hence, the embedded synchronization algorithm proves to be capable of yielding accurate estimates of mode shapes. As shown in Figure 11, in setup 1, only the right span is instrumented; for illustration purposes, the mode shape of the left span (plotted with gray line) is assumed to be symmetric or antisymmetric (depending on the results of setup 2) to the mode shape of the right span. Asymmetries observed between the two girders and/or between the two spans (for setup 2) are mainly attributed to coupling between the first and second mode as well as between the third and fourth mode due to the modal peaks being closely spaced. In addition, for this bridge, the relatively low resolution of the accelerometer results in a high ratio of lowest detectable acceleration over maximum oscillation amplitude, which, in turn, leads to less accurate detection of the modal peaks.

5. Summary and conclusions

Reliable and accurate synchronization in wireless sensor networks remains an open question within the field of computer science. In this paper, an embedded synchronization algorithm implemented into a prototype wireless SHM system has been presented. The proposed embedded synchronization algorithm complements embedded peak-picking algorithms for frequency-domain operational modal analysis. Data synchronization is based on the relationship between the phase angles at modal peaks of Fourier amplitude spectra of acceleration response data sets collected from different sensor nodes. Time lags between one specific sensor node, designated as “reference node”, and the rest of the wireless sensor nodes are detected following the exchange of phase angles at modal peaks between the reference node and the rest of the sensor nodes. The calculation of the time lags is performed on board the wireless sensor nodes by exploiting the inherent embedded processing capabilities of the sensor nodes. Subsequently, the sensor nodes synchronize the acceleration response data sets according to the time lags.
The wireless SHM system materializing the embedded synchronization algorithm, has been implemented and validated through shake table laboratory tests on a shear frame structure and through field tests on a pedestrian overpass bridge. The purpose of the laboratory tests has been to investigate the applicability of the wireless SHM system under controlled excitation with minimal external interference, whereas the field tests have been conducted with an aim to test the SHM system under actual operational conditions with no control over the input excitation. The results from the laboratory tests have shown good agreement between the mode shapes extracted from the synchronized acceleration response data sets and the expected mode shapes calculated through numerical analysis. The lower level of accuracy in the third extracted mode shape (compared to the corresponding numerical mode shape) is attributed to the mode not being adequately excited. In the field tests, the mode shapes extracted after applying the embedded synchronization algorithm have been compared to results from a previous study on the bridge using seismographs synchronized with GPS. The comparison has shown a satisfactory agreement between the results obtained by the prototype SHM system designed to implement the embedded synchronization algorithm and the results of the previous study. Potential discrepancies between the aforementioned results as well as deviations from symmetry in mode shapes expected to be symmetric are attributed to the coupling of closely-spaced vertical bending and torsional modes as well as to the high noise floor of the accelerometer with respect to the oscillation amplitude of the bridge. Future research will focus on the statistical performance assessment of the embedded synchronization algorithm implemented into the prototype wireless SHM system and on exploiting other features of the Fourier phase spectrum for detecting time lags.

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