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A frequency domain approach for estimating relative time lag between vibration measurement data

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ABSTRACT

The synchronicity of the measurement data at different locations of a structure is essential to structural health monitoring. Sometimes, however, non-synchronicity may occur in them. A frequency domain approach is proposed for the estimation of the relative time lag between vibration measurement data. Making use of the mapping between a relative time lag in the time domain and a phase angle shift in the frequency domain, the relative time lag between either two outputs of a structure is determined by finding a mode where the actual phase angle between them is ideally zero and then calculating the perturbed phase angle that corresponds to the modal frequency of the selected mode. To address the problem of non-uniqueness of solutions, the slope of the phase angle curve is employed to identify the actual relative time lag from a pool of candidates. Extensive validations have been carried out with the use of filed measurement data. Asynchronous acceleration data recorded during a ship-collision of the Jiangyin Bridge were employed to examine its capability to fulfill correct identification of relative time lag. Synchronous acceleration data of the Canton tower under ambient excitations were exploited to test its capability to avoid false-positive identification of relative time lag. The proposed frequency domain approach achieved a satisfactory performance in the identification of relative time lag for both asynchronous and synchronous measurement data.

1. Introduction

Over the past two decades, the importance of structural health monitoring (SHM) of civil engineering structures has been well recognized [1–6]. The aim is to trace structural health conditions from reliably measured data with the help of evaluation techniques in conjunction with inductive reasoning and experience. To this end, the synchronicity of the measurement data at different locations of a structure is essential. For example, the system identification, which is usually an indispensable part of SHM, requires synchronous measurement data from multiple locations of a structure. Otherwise, erroneous results may be obtained. A direct consequence is that the phase information among them, which is considered as an important structural performance and damage indicator, can contain significant errors [7–12]. As a result, time synchronization has been the subject of intensive research in the wireless sensor networks (WSNs) community [13–17]. It arises in WSNs because of the fact that each sensor node in the network has an independent processor with its own local clock, which is not neces-

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sarily synchronized with the clocks of other sensor nodes. Furthermore, the non-simultaneity in sensing start-up among sensors, differences in sampling frequency among sensor nodes, and fluctuation of sampling frequency over time of each individual sensor node may also lead to the imperfect time synchronization in WSNs. To date, time synchronization protocols have been extensively investigated as a solution to the time synchronization problem in WSNs. Typical examples include RBS (Reference Broadcast Synchronization) [18], TPSN (Time-sync Protocol for Sensor Networks) [19], FTSP (Flooding Time Synchronization Protocol) [20], PulseSync (Pulse Synchronization Protocol) [21], μ-Sync [22], TSRTS (Tree Structured Referencing Time Synchronization) [23], and 2LTSP (Long term and Large scale Time Synchronization Protocol) [24]. Nevertheless, even when the protocols are employed in WSNs, completely synchronized measurements are not guaranteed. As for tethered sensor system, non-synchronicity may also occur in the measurement data though the time synchronization is thought to be much easier. In some cases, therefore, appropriate post-processing of the measurement data to eliminate the adverse effects of the synchronicity faults is needed.

To correct the time synchronization errors, a direct intuition suggests synchronizing the asynchronous measurement data by identifying the relative time lag between them. In this regard, however, limited studies have been reported in the literature so far. Lei et al. [25] proposed two algorithms for time synchronization of measurement data, i.e., an ARX (autoregressive with exogenous input) model for the estimation of the time delay between an output signal and input signals, and an ARMAV (auto-regressive moving average vector) model for two output signals. The method fits the measurement data to an appropriate mathematical model to the maximal extent, which usually involves highly complex computations for large and complex systems. Furthermore, the accuracy of the analysis depends on the order of the model which is difficult to determine. To assess the time synchronization accuracy of WSNs, Lynch et al. [26] proposed the use of minimum error norm between a wireless sensor signal and a reference tethered signal to find the relative time lag between them. Likewise, Shen et al. [27] employed the cross correlation function between wireless and tethered sensor data to obtain the relative time lag between them. The cross correlation function had also been utilized to estimate the time shift between a received signal and a known transmitted signal, which is used for the localization of sensor nodes in WSNs with the time-of-arrival method [28]. These methods rely on the waveform similarity or correlation between two time series which are in fact the same except for the existence of a time gap between them. Their usefulness may degrade if they are applied to align two time series that are measured at two different locations of a structure. Assuming the phases of the fundamental mode of a structure are identically zero, Bernal [29] used the time shifts needed to correct these phases to zero to realign the asynchronous output. To allow for the deviation of these phases from zero that is caused by the non-proportional damping, a threshold on the amplitude weighted mean of the absolute phases, above which synchronicity correction is activated, was proposed. The applicability of this approach, to some extent, is restricted because of the fact that the phases of the fundamental mode may not be identically zero. In summary, the time lag estimation algorithms for asynchronous measurement data are still scarce in the literature. Furthermore, it is worth noting that the time synchronization algorithm proposed in prior studies was tested only on simulation platform or in laboratory experiments. Different from the testing data acquired in ideal settings, the field measurement data usually contains more uncertainties, which may degrade the performance of the algorithms. As a result, it is more desirable that asynchronous measurement data of real civil engineering structures recorded under noisy environment would be available for the performance evaluation of the time synchronization approach.

In recognizing that a delay in the time domain maps to a phase shift in the frequency domain, it is therefore possible to identify the relative time lag between two time series inversely from the change in the phase angle between them. On this ground, this study proposes a frequency domain approach for the estimation of the relative time lag between vibration measurement data. First, the cross power spectral density (CPSD) is employed to find the phase angle between two time series. The relative time lag between them is then inversely identified from the phase angle shift. The complication arising from the fact that more than one candidate for the actual relative time lag can be inversely obtained is bypassed by making use of the slope of the phase angle curve of the CPSD. To test the performance of the proposed approach for the estimation of relative time lag, extensive validations are conducted with the use of the filed measurement data. Asynchronous acceleration data recorded during a ship-collision of the Jiangyin Bridge are employed to examine its capability to fulfill the correct identification of relative time lag. Synchronous acceleration data of the Canton tower under ambient excitations are exploited to test its capability to avoid false-positive identification of relative time lag.

2. Frequency domain approach

In this study, the civil engineering structure is assumed to behave as a linear system. As the vast majority of the structures are weakly damped, the assumption of proportional damping, i.e., the damping is distributed over the structure in the same way as the mass and stiffness are, is often made [30]. Likewise, this study also assumes that the structure is classically damped. Under this assumption, the mode shapes of a structure are purely real in theory [8,17]. Accordingly, the phase angle between any two synchronous outputs of a structure is either 0 (in-phase) or $\pm\pi$ (out-of-phase) at the modal frequencies of the structure. If they are asynchronous, a relative time lag between them will map to a change in the phase angle between them, indicating that the relative time lag can be inversely identified from the change of the phase angle. A straightforward approach to determine the relative time lag between either two outputs of a structure is to find a mode where the actual phase angle between them is ideally zero and then calculate the phase angle perturbed by the relative time lag that corresponds to the modal frequency of the selected mode. The details of the proposed approach are elaborated as follows.