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# Offline synchronization of data acquisition systems using system identification

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ABSTRACT

This paper presents a technique for offline time synchronization of data acquisition systems. The technique can be applied when real-time synchronization of data acquisition systems is impossible or not sufficiently accurate. It allows for accurate synchronization based on the acquired dynamic response of the structure only, without requiring a common response or the use of a trigger signal. The synchronization is performed using the results obtained from system identification, and assumes linear dynamic behavior of the structure and proportional damping of the structural modes. A demonstration for a laboratory experiment on a cantilever steel beam shows that the proposed methodology can be used for accurate time synchronization, resulting in a significant improvement of the accuracy of the identified mode shapes.



## 1. Introduction

Continuous health monitoring of civil engineering structures becomes more and more important. Assessing the health of a structure based on its dynamic response generally requires synchronous response measurements. The use of multiple data acquisition systems is often necessary, due to the large number of acquired channels, the large distance between sensors, or the need for heterogeneous sensor data [1]. In this case, the different data acquisition systems must be synchronized. Several techniques for real-time synchronization of measurement systems have been proposed so far. Amongst these techniques are time stamping through GPS [2], and synchronization through fiber optical cables or radio communication. Currently, monitoring systems consisting of multiple wireless sensors are being developed [3–7]. Two main challenges for wireless monitoring systems consist of increasing the battery life time and securing proper (wireless) time synchronization. Several time synchronization protocols for wireless sensor networks have been developed [8–10], each of them characterized by different accuracy, efficiency in power usage, and efficiency in required memory.

When direct time synchronization of data acquisition systems is impossible, or when the accuracy of the synchronization is insufficient, offline synchronization of acquired vibration data might be required. When the same response quantity can be measured by multiple data acquisition systems, offline synchronization can be easily performed by applying correlation techniques [11] or by calculating the transfer function that relates both measured signals [12]. The simultaneous acquisition of a common response quantity is not always possible, for example when a network of multiple wireless sensors at different locations on the structure is used.

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This paper presents a technique that allows for time synchronization of data acquisition systems based on the results obtained from system identification. The technique assumes linear time-invariant dynamic behavior of the structure over the measurement duration and proportional damping of the structural modes. The time synchronization is based on a phase shift of the identified mode shapes, which results from the synchronization time lag. The technique allows for accurate synchronization. The main advantage of the proposed synchronization technique is that it does not require capturing a common response by the different acquisition systems, which is an important benefit when dealing with wireless sensor networks.

The paper is outlined as follows. Section 2 shows that a synchronization time lag results in a phase shift of the identified mode shapes, whereas the identified natural frequencies and modal damping ratios are unchanged. Next, Section 3 demonstrates how the findings in Section 2 can be applied for offline synchronization of data acquisition systems. The data used in the demonstration consist of measured accelerations and strains obtained from a laboratory experiment on a cantilever steel beam. Finally, in Section 4, the work is concluded.

## 2. Mathematical background

Consider two response signals $d_1(t)$ and $d_2(t)$ obtained from sensors installed at arbitrary locations on the structure. The signals may correspond to different response quantities, e.g. acceleration or strain. Under the assumption of linear system behavior, the Laplace transform of the response signals, $d_1(s) \in \mathbb{C}$ and $d_2(s) \in \mathbb{C}$, are related through the transmissibility function $T(s) \in \mathbb{C}$ as follows [13]:

$$d_1(s) = T(s)d_2(s) \tag{1}$$

where $s \in \mathbb{C}$ is the Laplace variable [14]. Furthermore, the Laplace transform of the response signals $d_1(s)$ and $d_2(s)$ is related to the Laplace transform of the load vector $\mathbf{p}(s) \in \mathbb{C}^{n_p}$ through the transfer function matrices $\mathbf{H}_1(s) \in \mathbb{C}^{1\times n_p}$ and $\mathbf{H}_2(s) \in \mathbb{C}^{1\times n_p}$, respectively, as given by the following equations:

$$d_1(s) = \mathbf{H}_1(s)\mathbf{p}(s) \tag{2}$$

$$d_2(s) = \mathbf{H}_2(s)\mathbf{p}(s) \tag{3}$$

It assumed here that $n_p$ loads are acting on the structure. The number of loads and their location is not important for the derivation following next, however. Under the assumption that the response of the structure within a certain frequency range of interest is well approximated by a limited number of structural modes ($n_m$ modes), and assuming in addition proportional damping, the transfer function matrices $\mathbf{H}_1(s)$ and $\mathbf{H}_2(s)$ are given by:

$$\mathbf{H}_1(s) = \sum_{m=1}^{n_m} \frac{s^{q_1}\phi_{d_1 m}}{s^2+2\xi_m\omega_m s+\omega_m^2}\boldsymbol{\phi}_{pm} = \sum_{m=1}^{n_m} s^{q_1}\phi_{d_1 m}\mathbf{H}'_m(s) \tag{4}$$

$$\mathbf{H}_2(s) = \sum_{m=1}^{n_m} \frac{s^{q_2}\phi_{d_2 m}}{s^2+2\xi_m\omega_m s+\omega_m^2}\boldsymbol{\phi}_{pm} = \sum_{m=1}^{n_m} s^{q_2}\phi_{d_2 m}\mathbf{H}'_m(s) \tag{5}$$

where $\mathbf{H}'_m(s) = \boldsymbol{\phi}_{pm}/(s^2+2\xi_m\omega_m s+\omega_m^2)$, with $\boldsymbol{\phi}_{pm} \in \mathbb{R}^{1\times n_p}$ the vector of mode shape components corresponding to mode $m$ at the $n_p$ force locations. $\omega_m$ and $\xi_m$ are the undamped natural frequency and the modal damping ratio of mode $m$, respectively. $\phi_{d_1 m}$ and $\phi_{d_2 m}$ are obtained by selecting the component of the mode shape vector corresponding to mode $m$ at the sensor locations of $d_1$ and $d_2$, respectively. The integers $q_1$ and $q_2$ equal 0 for displacement or strain measurements, 1 for velocity measurements, and 2 for acceleration measurements.

The system has $2n_m$ poles, occurring in complex conjugate pairs, $\lambda_{m1}$ and $\lambda_{m2}$ ($m = 1, \ldots, n_m$), given by the following expression [15]:

$$\lambda_{m1,2} = -\omega_m\xi_m \pm i\omega_m\sqrt{1-\xi_m^2} \tag{6}$$

where $i = \sqrt{-1}$. The poles $\lambda_{m1}$ and $\lambda_{m2}$ correspond to the natural frequency $\omega_m$ and modal damping ratio $\xi_m$ of mode $m$. When the transfer function matrices in Eqs. (4) and (5) are evaluated at a system pole, i.e. $s = \lambda_{m1}$, only the corresponding mode $m$ contributes to the system response [16], and the following expressions are obtained:

$$\mathbf{H}_1(\lambda_{m1}) = \lambda_{m1}^{q_1}\phi_{d_1 m}\mathbf{H}'_m(\lambda_{m1}) \tag{7}$$

$$\mathbf{H}_2(\lambda_{m1}) = \lambda_{m1}^{q_2}\phi_{d_2 m}\mathbf{H}'_m(\lambda_{m1}) \tag{8}$$

Combination of Eqs. (7) and (8) directly yields:

$$\mathbf{H}_1(\lambda_{m1}) = \frac{\lambda_{m1}^{q_1}\phi_{d_1 m}}{\lambda_{m1}^{q_2}\phi_{d_2 m}}\mathbf{H}_2(\lambda_{m1}) \tag{9}$$