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Operational modal analysis using asynchronous data for frequencies and mode shapes identification

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Abstract

The monitoring and the assessment of structures (SHM), in order to ensure human and material safety, is a very important issue in civil engineering. The mainly used SHM techniques are based on the study of the vibratory behavior of the structure by accelerometric or velocimetric measurement. Using operational modal analysis techniques (OMA), modal identification involving natural frequencies and mode shapes can be carried out. In order to do so, the response of the structure to ambient excitations is measured using several sensors. Conventional modal identification approaches use synchronous data, in which different channels are sampled at the same sampling rate and the same time window by means of long cables, GPS and real time clock. Modal analysis test can be conducted more flexibly if it could be performed even if the measured data are not synchronised. This research investigates the impact of asynchronous data on the identification of eigenfrequencies and mode shapes using operational modal analysis methods, namely the Stochastic Subspace Identification (SSI) and the Frequency Domain Decomposition (FDD), and its correction.

Keywords: Structural Health Monitoring (SHM), Asynchronous data, Operational Modal Analysis (OMA)

1 Impact on the identification of eigenfrequencies

The stochastic subspace identification method allows identification of eigenfrequencies. This algorithm temporally correlates the accelerations coming from several sensors supposed to be synchronized. The correlation between two responses $x_{ik}(t)$ and $x_{jk}(t)$ is defined by [1]:

$$R_{ijk}(T) = E[x_{ik}(t+T) x_{jk}(t)] \quad (1)$$

Where E is the mathematics expectation.

$x_{ik}(t)$ is the solution of the equation of motion and can be written as [2]:

$$x_{ik}(t) = \sum_{r=1}^n \Phi_i^r \Phi_k^r \int_{-\infty}^t f_k(\tau) g^r(t-\tau) d\tau \quad (2)$$

With $g^r(t) = \frac{1}{m^r w_d^r} e^{-\xi^r w_n^r t} \sin(w_d^r t)$ and $w_d^r = w_n^r \sqrt{(1-\xi^{r2})}$ the damped natural frequency. Φ_i^r and Φ_k^r are respectively the i^{th} and the k^{th} mode shape components of r^{th} mode. f is a white noise excitation.

By replacing equation 2 in equation 1, the correlation between $x_{ik}(t)$ and $x_{jk}(t)$ becomes:

$$R_{ijk}(T) = \sum_{r=0}^n \frac{\Phi_i^r A_j^r}{m^r w_d^r} e^{-\xi^r w_n^r T} \sin(w_d^r T + \Theta^r) \quad (3)$$

where A_j^r et Θ^r are constants [2]. w_n^r is the natural frequency, ξ the damping ratio and m^r the mass. Assuming now that the response x_{jk} is recorded with a delay δt relative to x_{ik} , the correlation function becomes:

$$R_{ijk}(T) = \sum_{r=0}^n \frac{\Phi_i^r A_j^r}{m^r w_d^r} e^{-\xi^r w_n^r T} e^{-\xi^r w_n^r \delta t} \sin(w_d^r T + (w_d^r \delta t + \Theta^r)) \quad (4)$$

By comparing equation 4 and 3, one can see a phase shift between the two expressions equal to $w_d^r \delta t$. However, the eigenfrequencies w_d^r are not influenced by the time-delay in the measurements. Therefore, if the time-delay between the signals is unknown, it is possible to identify the eigenfrequencies of the studied system, provided that the measurements are made under the same conditions.

2 Impact on the identification of mode shapes

The main step in the frequency domain decomposition (FDD) method is to compute the power spectral density matrix ($G_{yy}(jw)$) from the structure's response. By decomposing $G_{yy}(jw)$ into singular values, it is possible to estimate the mode shape from the first eigenvector of the left matrix U of the singular decomposition [3].

$$G_{yy}(jw_m) = U \Sigma U^t \quad (5)$$

Where Σ contains the singular values of G_{yy} .

According to Kerschen and Golinval [4], the singular value decomposition of the G_{yyjw} can be calculated by performing the eigenvalue decomposition as follows:

$$G_{yy}(w_m) G_{yy}^*(w_m) = U \Sigma \Sigma^* U \quad (6)$$

where $*$ denotes the transconjugate of a matrix. Σ and U are respectively the matrix of singular values and the left singular values decomposition matrix. In the case of a vibrational mode ($w = w_m$) and in the case where the n sensors are not synchronized, the matrix $G'_{yy}(w_m)$ can be written in the following form [5]:

$$G'_{yy}(jw_m) \approx P G_{yy}(jw_m) P^* \quad (7)$$

Where P is the matrix of errors due to desynchronization.

The identification of mode shapes can take place by decomposing in eigenvalues $G'_{yy} G'_{yy}^*$ as follows:

$$G'_{yy} G'_{yy}^* \approx P G_{yy}(jw_m) P^* P^* G_{yy}^*(jw_m) (P^*)^* \quad (8)$$

$$\approx U' \Sigma \Sigma^* U'^* \quad (9)$$

Analogously to the case of perfectly synchronized sensors, the first vector U'_1 of U' is an estimation of the mode shape of the same mode. The normalized modal deformed with respect to displacement, taking the r sensor as a reference, can be written in the following form [5]:

$$U'_1 \approx \begin{pmatrix} \frac{e^{iw_m(t_1-t_1)} U_{1,1}}{e^{iw_m(t_r-t_1)} U_{r,1}} \\ \vdots \\ \frac{e^{iw_m(t_k-t_1)} U_{k,1}}{e^{iw_m(t_r-t_1)} U_{r,1}} \\ \vdots \\ \frac{e^{iw_m(t_n-t_1)} U_{n,1}}{e^{iw_m(t_r-t_1)} U_{r,1}} \end{pmatrix} = \begin{pmatrix} e^{iw_m(t_1-t_r)} \frac{U_{1,1}}{U_{r,1}} \\ \vdots \\ e^{iw_m(t_k-t_r)} \frac{U_{k,1}}{U_{r,1}} \\ \vdots \\ e^{iw_m(t_n-t_r)} \frac{U_{n,1}}{U_{r,1}} \end{pmatrix} \quad (10)$$

From equation 10, it is clear that the presence of time-delay introduces a phase shift to each of the mode shape components, which is reflected in the term $e^{iw_m(t_n-t_r)}$ for the i^{th} component. This difference will result in the maximum amplitude at different measurement points being reached at different times, thus causing a change of sign and amplitude. The generated phase shift, which is equal to $w_m(t_n - t_r)$, becomes more and more important for higher order modes [6]. In the particular case where the measurements are carried out under the same conditions, and provided that the delay does not exceed the duration of the measurement, it is possible to estimate this delay from the generalized intercorrelation function and thus adjust the sign of the modal deformed. Generalized intercorrelation has the expression [7]:

$$R_{r_1 r_2} = \int_{-\infty}^{+\infty} \frac{G_{r_1 r_2}}{|G_{r_1 r_2}|^\beta} e^{j2\pi f \tau} df \quad (11)$$

where $G_{r_1 r_2}$ is the power spectral density, τ is the delay between the two signals r_1 and r_2 , and $beta = 0.8$. The time-delay corresponds to [8]:

$$\tau = \tau_{max}\{R_{r_1 r_2}\} \quad (12)$$

In the case where several sensors are considered, it is necessary to calculate the delay of each sensor with respect to a reference sensor.

3 Application on accelerometric measurements on the Ophite tower

The building considered in this study is the Ophite Tower, located in Lourdes, France. It is a reinforced concrete structure composed of 19 storeys. It was built in 1972 and it is permanently instrumented with 24-channel system and an acquisition station. The acceleration responses in the longitudinal direction (L) is used over a period of 80 seconds [9]. These accelerations come from 5 sensors located on floor 1, 5, 9, 13, 16, and 19. The time-delay between the signals is between 5 and 20 seconds and is introduced in a random manner. The sensor at storey 19 is taken as a reference sensor.

3.1 Eigenfrequencies identification

the stochastic subspace identification method allows the identification the eigenfrequencies with a very high accuracy. Using asynchronous data and synchronous data the frequencies identified are extremely close (Table 1).

Freq.[Hz](syn.)	Freq.[Hz](Asyn.)	erreur %
1,70	1,70	0
2,25	2,25	0
5,76	5,77	0,17

Table 1: Eigenfrequencies identification of the Ophite tower - Comparison between results from synchronous data and asynchronous data

3.2 Mode shapes identification

The FDD method showed more sensitivity to the time-delay. In fact, the latter caused a sign and an amplitude change proportional to the delay in the mode shape components. Mode shapes have been corrected using the generalized intercorrelation method (Fig.1)

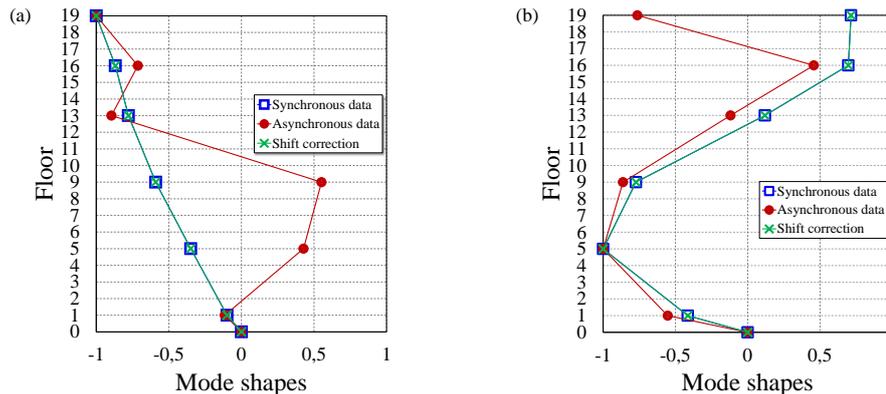


Figure 1: Mode shapes identification using synchronous, asynchronous and corrected data - component L: (a) 1st bending mode, (b) 2nd bending

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