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SYNCHRONIZATION OF AMBIENT VIBRATIONS DATA FROM TESTS ON LARGE BUILDINGS OBTAINED BY MULTIPLE DATA ACQUISITION SYSTEMS

Salman Saeed[1] and Luc E. Chouinard[2]

ABSTRACT

A major problem in planning ambient vibration tests for large buildings is synchronous acquisition of data. It is of vital importance that during a single test, data at all the nodes be recorded synchronously. However, when sensors have to be installed at locations that are at far ends of buildings, the provision of long connection cables between the sensors and the data acquisition system (DAS) becomes unfeasible. It then becomes necessary to utilize more than one set of DAS. The use of multiple DAS overcomes the physical and economical limitations to ambient vibration tests in large buildings. However, the data thus acquired usually has a lag, arising from time drifts within the clocks of different DAS, that is often impossible to determine. This study aims at investigating errors that may arise in the identification of mode shapes obtained from asynchronous data. A methodology involving the use of phase angle information to synchronize the data obtained from separate DAS is proposed. The proposed methodology is applied to simulated data and the results are presented. By accurately identifying mode shapes from asynchronous data, this novel approach overcomes a major hurdle in the deployment of multiple DAS. Therefore, the cost effective and flexible sensor architecture offered by multiple DAS can be readily exploited in planning for ambient vibration tests for large buildings.

Introduction

Modal Analysis refers to experimental procedures that are used in system identification to describe the dynamic behavior of test structures. Modern computing technology and the development of highly sensitive and precise instrumentation has led to many advances in modal analysis procedures. Classically these methods involved artificial excitation of a test structure by external source(s) and the simultaneous measurements of input forces and structural responses. Using these measurements, the experimental model was obtained by various parameter estimation methods. The frequency response functions (FRFs) in the frequency domain or impulse response functions (IRFs) in the time domain are usually the basis of system identification algorithms, which produce accurate estimates of modal parameters provided that the signal-to-noise ratio of the measurement data is high enough (Bahlous 2009).

However, it is difficult in practice to precisely measure all the excitation forces that are applied to a structure and in some cases it is not possible to apply an artificial excitation. In most cases, it is impossible to measure ambient excitations and the structural responses are the only parameters that can be reliably measured. This is particularly true for large and flexible buildings and bridges where it is extremely challenging and costly to provide controlled excitation for significant levels of response.

[1]Graduate Student, Dept. of Civil Engineering & Applied Mechanics, McGill University, Montreal, QC, Canada
[2]Associate Professor, Dept. of Civil Engineering & Applied Mechanics, McGill University, Montreal, QC, Canada

Ambient Vibration Tests (AVTs), also known as in-operation modal analysis or simply Operational Modal Analysis (OMA), are a new generation of System Identification procedures that rely on random in-operation dynamic excitations or naturally occurring ambient excitations. For these methods, only the output of the system is observed in response to unmeasured ambient excitations is assumed to be white noise.

Application of Ambient Vibration Tests to Civil Engineering Structures

For civil engineering structures, ambient vibration tests are preferred over forced vibrations because disturbances for occupants are avoided and the measured response is representative of the structural responses under natural excitations. An important advantage of AVT is the use of the ambient excitation caused by natural excitation sources such as wind, microtremors, traffic and occupancy, as opposed to the use of artificial excitation devices (large shakers, drop weights) which are expensive and impractical (Kramer 1999). Moreover, since ambient vibration tests do not interrupt service of the test structure (e.g., shutting down traffic during bridge testing), they can be used for long term continuous structural health monitoring. Ambient vibration tests have been successfully applied to a variety of structures (Peeters 1999, Hermans 1999, Ventura 2000, 2001 & 2002, Parloo 2003 and Reynders 2007).

Multi-Setup measurements

In practice, when surveying a large structure or when a high spatial resolution is required, measurements cannot always be performed for all DOFs simultaneously. In order to cover all potential DOFs of the structure, measurements have to be performed in different sequences and setups. The objective is to emulate data collection with a large number of sensors. For this purpose, data sets are recorded with sensors at different locations on the structure. Some of the sensors, called the reference sensors, are kept fixed, while the others are moved (the rovers). System identification is performed for each setup separately and the results are scaled and merged (assembled) to construct the complete eigen-structure. Parloo (2003) presents different methods to assemble individual setups. The method adopted in this study is the so-called non-parametric assembly approach, described in the following section, in which the re-scaling and assembling of different setups is performed before the system identification step.

Use of Multiple Data Acquisition Systems

Multi-setup AVT can be used with a few sensors to perform high spatial resolution surveys; however, all the reference and roving sensors must be connected to a single Data Acquisition System (DAS) to obtain simultaneous records. This measurement scheme requires long cables when the reference and roving sensors are located far apart. In certain cases, such as high rise buildings, it is virtually impossible to connect the sensors to a single DAS without interfering with the normal functions of the building, which undermines the advantage of AVT as being non-intrusive.

An alternative approach is to use multiple DAS or a set of sensors and eliminate the use of long cables. This reduces the cost of the test significantly and makes it possible to plan measurement campaigns with minimal disturbance to the occupants and operations in the building. However, such a setup requires that data records are synchronized. One way to synchronize is to adjust the internal clocks of the DAS with a common source (for example GPS satellite), and later crop the data from each sensor by utilizing the time stamps in the data files. Most DAS however, do not record the exact time with the data files, or in case of equipment used by the authors, the drift in the internal clocks desynchronizes them during the course of the test. In summary, it is very difficult and sometimes impossible to obtain synchronous data recording with multiple DAS. Non-synchronized data results in inaccurate and erroneous parameter estimation for the structural response.

In this paper, we discuss the effect of asynchronous data obtained from multiple DAS, on the estimation of modal parameters of buildings. This paper then proposes an algorithm which utilizes the phase angle at each DOF in the mode shapes, to estimate the time lag between the reference and roving sensors in each setup.

A simple numerical model with lumped masses is used to generate a data set to perform the study. This data is then de-synchronized by introducing a known time lag in each setup to simulate typical test conditions. The synchronization algorithm is then applied to the data and results are compared to the true numerical solution.

Simulations

Test Procedure and Data Processing

The test procedure adopted in this study utilizes two sensors, one reference sensor fixed in a location where contributions from most of the modes can be recorded, and one roving sensor which is moved to a different location in each setup. The data from the reference sensor is only used for scaling the data from each setup. Figure 1 shows a typical test procedure employed in this study.

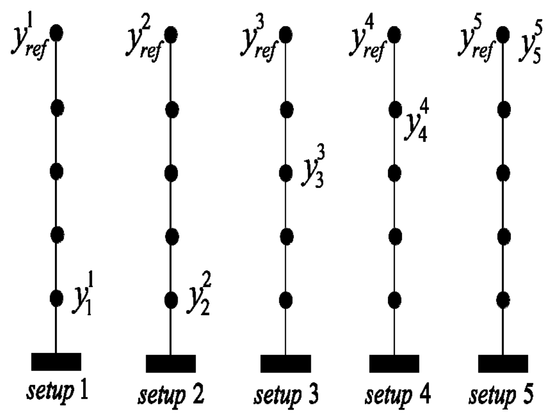


Figure 1 - Typical multi-setup test procedure

In the above figure, $y^k{}_{ref}$ and $y^k{}_j$ are the time series of the channels from reference sensor and roving sensor at jth node in *k*th (out of N) setup. The auto and cross spectral densities (CPSD) $Y^k_{ref,ref}(\omega)$, $Y^k_{ref,j}(\omega)$ and $Y^k_{j,j}(\omega)$ are computed for each test setup using the Welch's averaged, modified periodogram method of spectral estimation (Welch 1967).

The scaling matrix is computed by taking the average of CPSD of the reference channels from all setups, and scaling of each setup is done as follows:

$$Y_{ij} = Y^k_{ij} = Y^k_{i,j} \cdot \left[Y^k_{ref,ref}\right]^{-1} \cdot \left[\frac{1}{N}\sum_{m=1}^{N} Y^m_{ref,ref}\right] \tag{1}$$

All the scaled CPSD are then assembled into a global system spectral matrix, omitting the reference channels.

$$Y(\omega_i) = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_{15} \\ Y_{21} & Y_{22} & 0 & 0 & 0 \\ Y_{31} & 0 & Y_{33} & 0 & 0 \\ Y_{41} & 0 & 0 & Y_{44} & 0 \\ Y_{51} & 0 & 0 & 0 & Y_{55} \end{bmatrix} \quad (2)$$

The assembled system matrix is then decomposed by taking singular value decomposition.

$$[Y](\omega_i) = [U_i][S_i][\overline{U}_i]^T \quad (3)$$

Where $[U_i]$ is matrix of singular vectors and $[S_i]$ is a diagonal matrix of singular values. The peaks on plots of singular values give the modal frequencies and the corresponding singular vectors are the mode shapes.

Generating Data

A numerical model of a 5 storey shear building was constructed in SAP 2000®, with fixed base and lumped masses. Rotations at all joints and vertical translations are constrained and only the horizontal translations in X and Y directions are allowed. The resulting model has 10 DOF, 5 in each horizontal direction. Damping was neglected in the model. The eigen-frequencies and corresponding mode shapes are shown in Figure 1. Each node in the model is subjected to an independent white noise input applied at each DOF. To simulate the test conditions, 5 different load cases are defined, each with 10 independent white noise excitations. The output from each load case is considered a separate test setup, with the top node as reference. The output data consists of velocity time-histories consisting of 60000 data points (Δt = 0.01s (i.e. 100 Hz) for 600 seconds). This data is then treated by the system identification routines to extract system frequencies and mode shapes. Figure 1 shows the plot of the first singular values obtained from each setup individually and the assembled system. Table 1 lists the frequencies and mode shapes obtained by the system identification routines and their comparison with those obtained from SAP2000.

Introducing Time Lag / Asynchronous data

To simulate the test conditions a random time lag is introduced between the reference node and roving node data in each setup. The objective of the algorithm is to correctly determine these time lags for each setup. The data is again treated to extract modal information. Figure 3 and Table 2 show the SVD plots and extracted mode shapes, respectively, from asynchronous data. It is observed that the modal frequencies can still be accurately identified for each setup individually as well as for the assembled system. However, the mode shapes are not correctly identified.

Table 3 shows the first two fundamental modes in each direction and break-up of these complex mode shapes into their magnitudes and phase angles at each node for synchronous and asynchronous data. It can be noticed that in the case of synchronous data the phase angle is either 0 or 180 degrees, as should be the case for zero damping. While, the time lag in each setup introduces a random phase angle in the mode shapes. This information is exploited in order to determine the time lags in each setup.

Implementation of synchronization algorithm

The underlying concept of the synchronization algorithm is that the time lags for each setup are adjusted in order to make the phase angles at each node equal to 0 or 180 degrees for the first two natural frequencies of a building (in all cases, these are monotonic functions). To find the proper adjustment, the time series from the reference node is shifted in time increments relative to the time series from the roving node in each setup. Next, for each lag, the corresponding shifted time series are used to assemble the system matrix. Finally, using the results from singular value decomposition, the phase angle at each node is plotted as a function of the time lag for all setups (Figure 4). Using Phase Angle vs. Time Lag (PATL) plots of the reference setup, the time-lags corresponding to peaks and troughs that are common to the first two fundamental modes are identified and tagged as potential solutions to the time lag between DAS. Fixing the time lag at one of the solutions, PATL plots of the roving sensors are updated, and scanned for potential solutions. An additional criterion is imposed for filtering out the potential solutions in roving setups: only the phase angles that match with those of the reference setup are considered. When no solution is found for any of the roving setups, then the potential solution for the reference setup is discarded and the next candidate solution is selected and the procedure is repeated until a solution is found for all the setups. Figure 4 shows the PATL plots for all setups, the vertical lines show the time lags where the phase angle is 0 and 180 degrees for the first two mode shapes. These points correspond exactly to the time lags that were introduced in each setup. After correcting the times series for the lag, the analysis identifies the mode shapes without error.

Conclusions

Ambient Vibration Testing provides a fast and accurate method to determine the dynamic parameters of a building. A multi-setup approach is desirable when applied to the analysis of high-rise buildings and/or when only a limited number of sensors are available. In both cases, it may be difficult or impractical to connect all the sensors to the same data acquisition system and obtain synchronized data. The other option is to use separate data acquisition systems for each sensor which results in unsynchronized data sets. Analyses performed on unsynchronized data sets can accurately identify natural frequencies but fail in estimating the corresponding mode shapes. An approach for synchronizing data sets from different acquisition systems is proposed using the phase angles from the first two fundamental modes of a building. The use of this approach was demonstrated for a model where time lags were arterially introduced. In all cases, the proposed approach was successful in estimating the lag and reproducing the theoretical natural frequencies and mode shapes. This novel approach overcomes a major hurdle in the deployment of multiple DAS and allows the cost effective and flexible multi-setup sensor deployment architecture for any type of building.

Figures and Tables

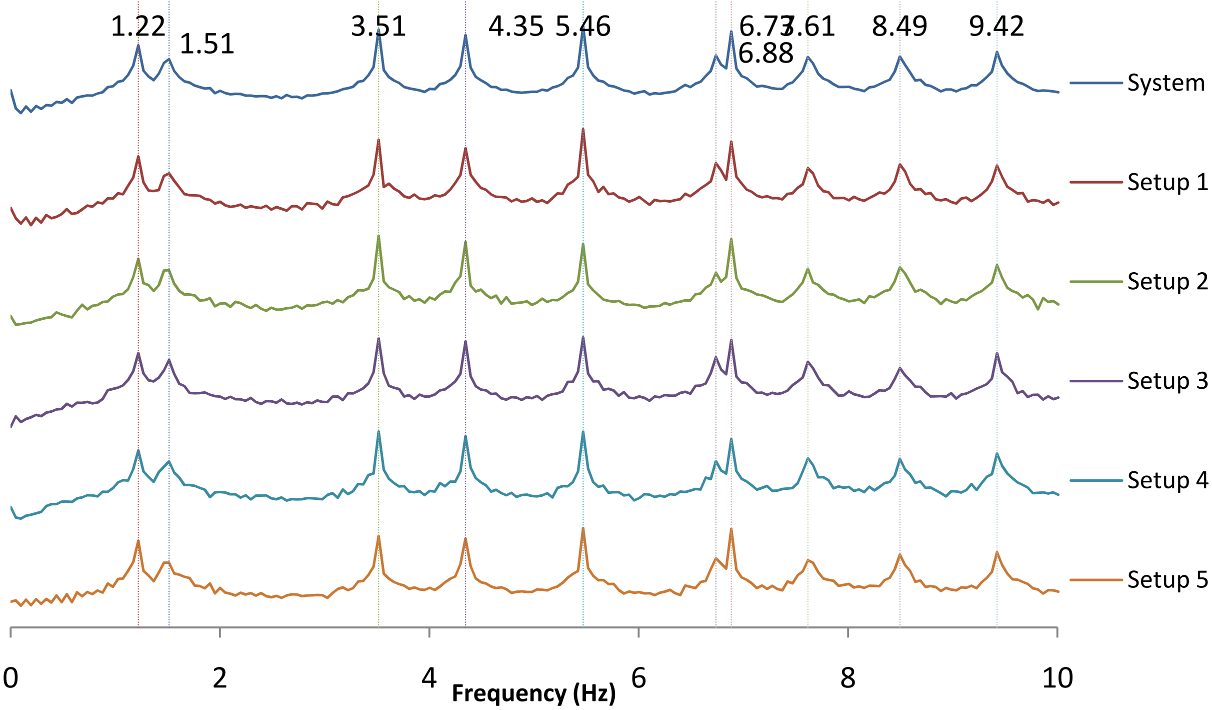


Figure 2. First singular values vs. frequency for the assembled system and for each setup, Synchronized Data

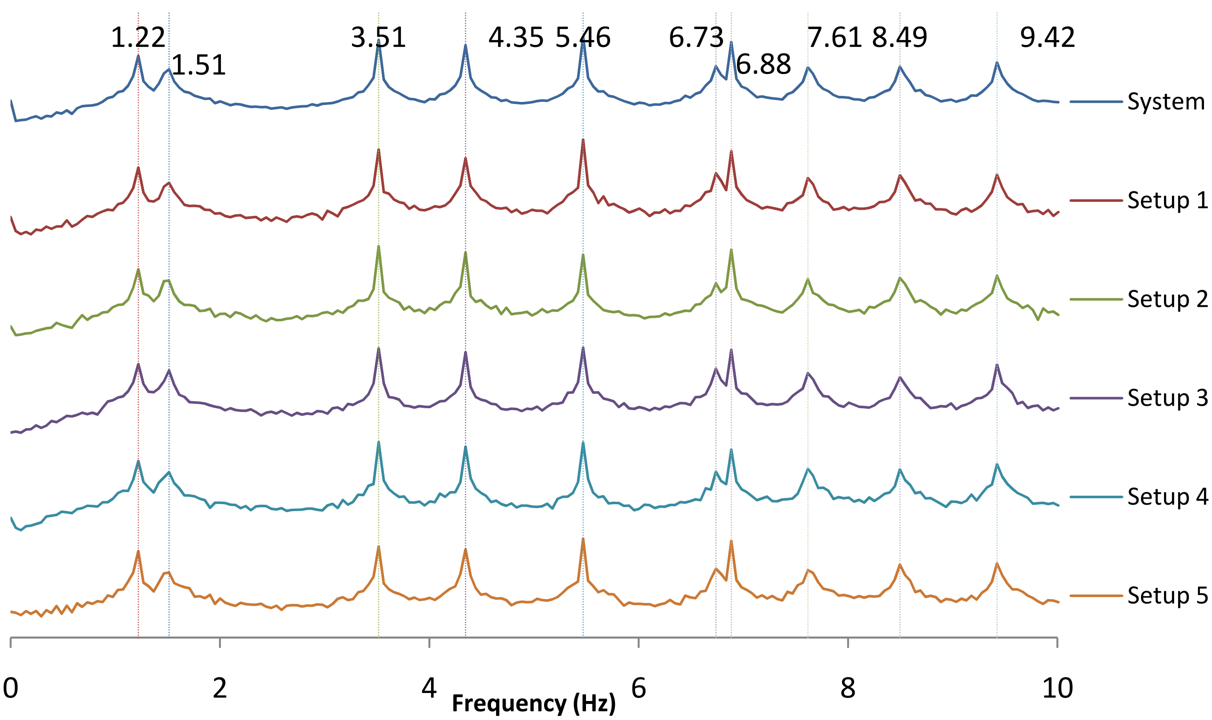


Figure 3. First singular values vs. frequency for the assembled system and for each setup – Un-synchronized data.

Table 1. Comparison of First 10 mode Shapes extracted from system Identification (solid lines) with those of SAP 2000 (dotted lines)

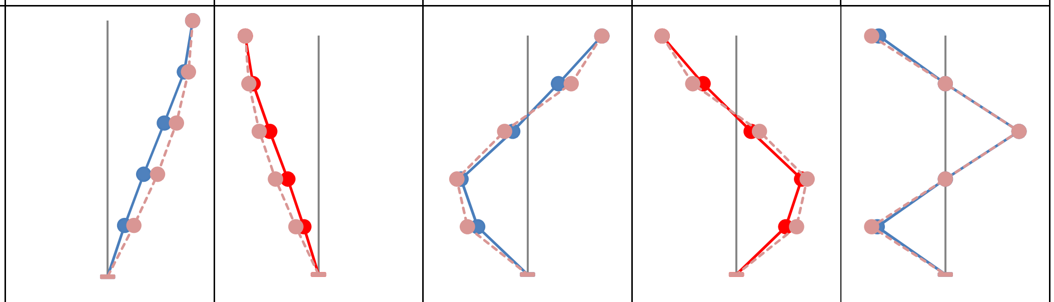
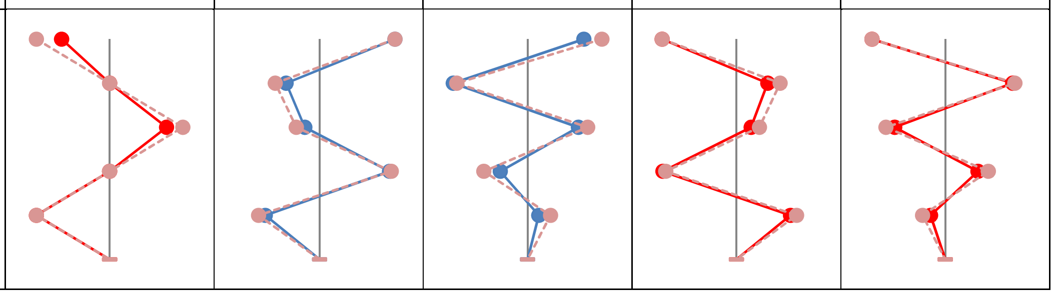
Frequency (Hz)	1.22	1.21	1.51	1.49	3.52	3.51	4.35	4.34	5.47	5.47
Mode	1		2		3		4		5	
Mode Shapes										
Frequency (Hz)	6.74	6.76	6.88	6.89	7.62	7.64	8.50	8.51	9.42	9.44
Mode	6		7		8		9		10	
Mode Shapes										

Table 2. Mode shapes extracted from unsynchronized data.

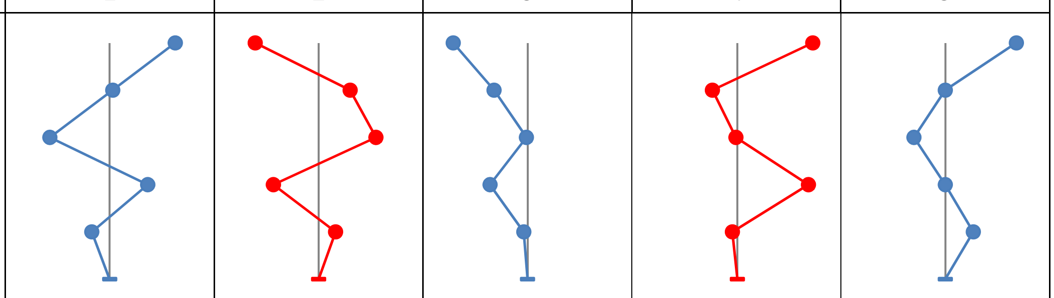
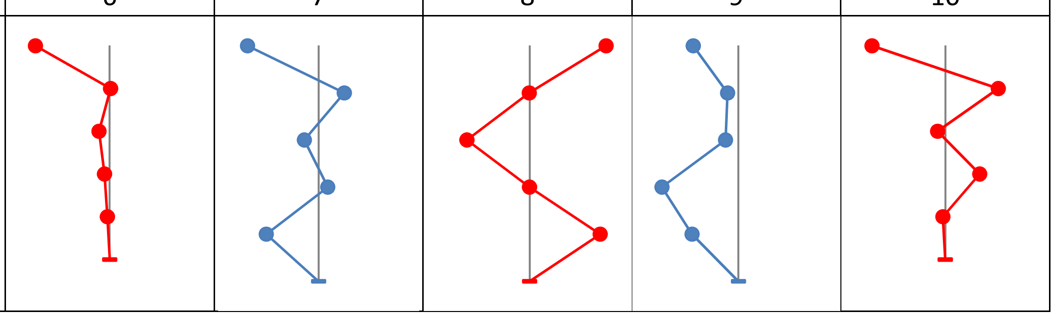
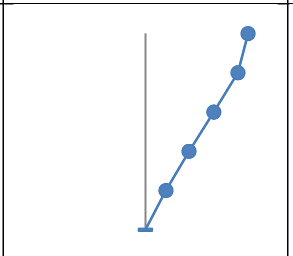
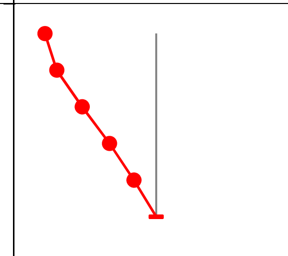
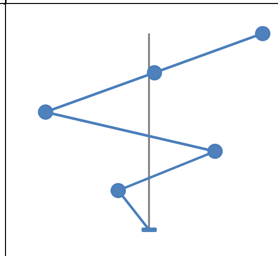
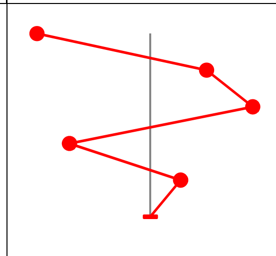
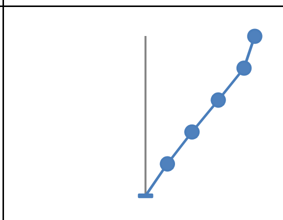
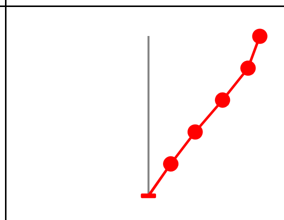
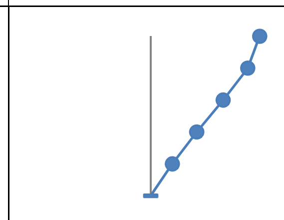
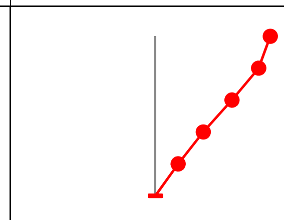
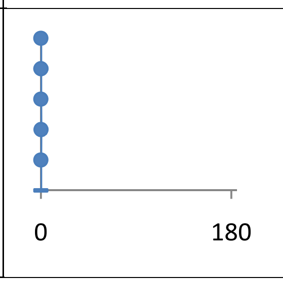
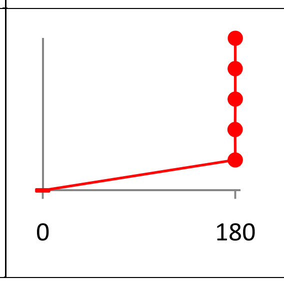
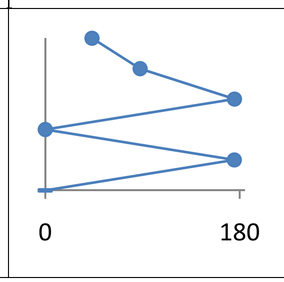
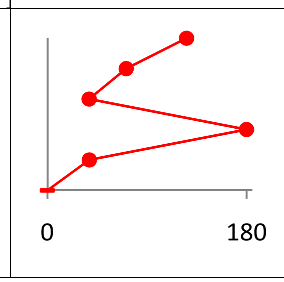
Frequency (Hz)	1.22	1.51	3.52	4.35	5.47
Mode	1	2	3	4	5
Mode Shapes					
Frequency (Hz)	6.74	6.88	7.62	8.50	9.42
Mode	6	7	8	9	10
Mode Shapes					

Table 3. Magnitudes and phase angles of complex mode shapes for the first two modes, for

synchronized and unsynchronized data

	Synchronized Data		Unsynchronized Data	
Mode	1	2	1	2
Mode Shapes				
Mode Shape Magnitudes				
Phase Angles				

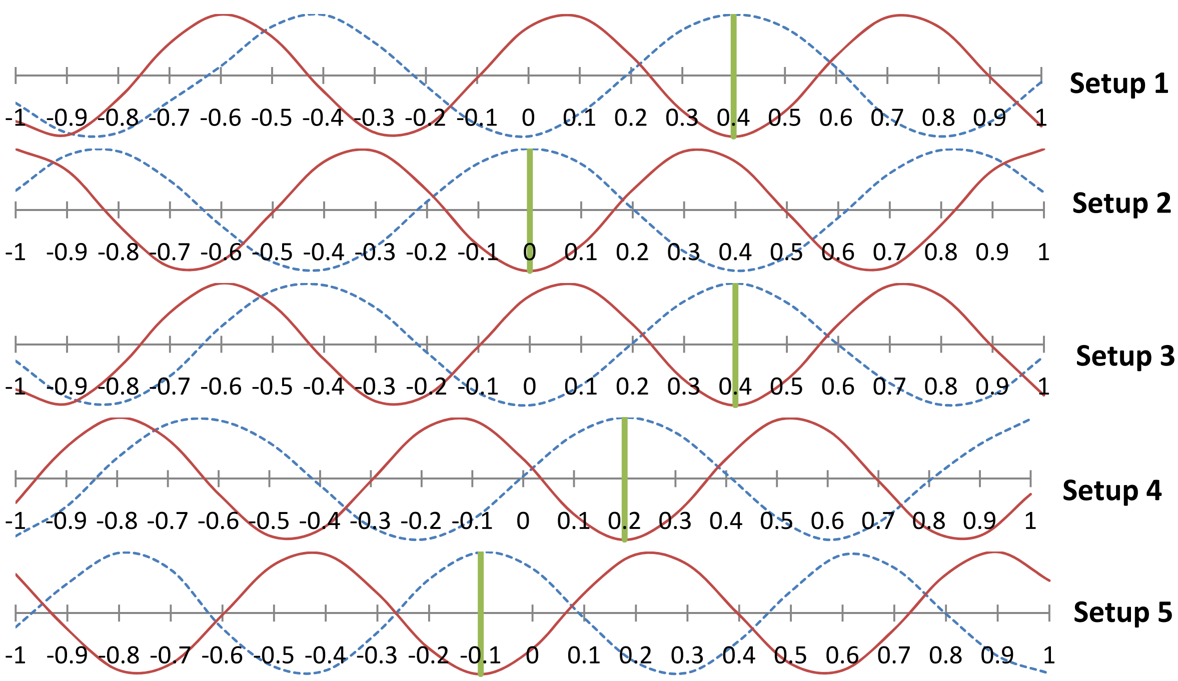


Figure 4. Phase Angle vs. Time Lag (PATL) plots for all setups, with solutions shown by vertical lines

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