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Modal identification using SMITM

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ABSTRACT

The objective of this paper is to introduce a Structural Modal Identification Toolbox for Matlab (SMITM) that has been recently developed to facilitate system identification of structural systems. SMITM is an integrated toolbox, supporting a user-friendly Graphical User Interface (GUI) for modal identification. In this paper, the results of several system identification methods are compared in terms of accuracy and efficiency. The toolbox is capable of performing several common system identification methods with a standardized process, which is composed of input, eigenvalue estimation, and post processing procedures. The toolbox can present the estimated modal parameters graphically, and conveniently store and recall the identification results. The implemented identification methods consist of several classes of system identification algorithms, including Eigensystem Realization Algorithm (ERA), Auto-Regressive Moving-Average method with eXogenous terms (ARMAX), and Stochastic Subspace Identification (SSI). The performance of SMITM was verified by identifying the modal parameters of Northampton Steel Bridge (NSB), using five identification algorithms. A set of ambient acceleration responses was collected using a Wireless Sensor Network (WSN), and a subset of the sensing nodes was selected to identify vertical and torsional modes of NSB. The comparison of identification results to examine the accuracy and efficiency of each method supports that the SMITM is applicable to identify civil infrastructures effectively.

INTRODUCTION

System identification is a widely-used Structural Health Monitoring (SHM) method, capable of estimating modal parameters of a system. The development of computing systems and sensor technology, such as the Wireless Sensor Network (WSN), has extended the applicability of system identification [1]. As a globally-based SHM technique, system identification plays a significant role in connecting the gap between numeric models and physical structures [2]. During the last three decades, numerous methods have been developed to accurately estimate modal parameters of civil infrastructures [3-7]. In order to estimate the performance of identification techniques, several studies have focused on comparing identified modal parameters for a set of input/output sensor data [8-10].

The demand has increased for a compact program that allows users to conveniently access an entire procedure and compare identification results, depending on the methods used. Recently, few research groups have focused on developing a system identification toolsuite as a part of SHM. Flynn et al. [11] has been introduced SHMTools, which is a Matlab® package that facilitates the construction of Structural Health Monitoring (SHM) processes. SHMTools provides more than 100 functions, which follow three main steps of SHM processes: 1) Data acquisition, 2) Feature extraction, and 3) Feature classification. System identification serves as a part of feature extraction, and Auto Regressive with eXogenous input (ARX) or Auto Regressive (AR) methods are utilized in this program. Reynders et al. [12] have developed MACEC ver. 3.2, which is toolbox for modal analysis of structures. The available methods for MACEC consist of a few classes of subspace identification and frequency response methods.

Chang et al. [13] have developed SMITM (Structural Modal Identification Toolbox for Matlab®) to provide a more sophisticated and comprehensive program, appropriate for system identification of civil infrastructures. SMITM handles various system identification methods, including Eigensystem Realization Algorithm (ERA), ERA-Observer Kalman filter Identification (OKID), ERA-Natural Excitation Technique (NExT), ERA-NExT-AVG, Structural Realization using Information Matrix (SRIM), ARX/AR, and Numerical algorithms for Subspace State Space System IDentification (N4SID) [14-19]. In order to systematically manage the eigenvalue estimation results from different methods, the program was created with three main procedures: 1) pre-processing, 2) eigenvalue estimation, and 3) post-processing procedures. SMITM has been fitted with a Graphical User Interface (GUI), allowing the user to conveniently select identification options and define variables.

This paper presents the use of newly developed software, SMITM, and the study of its applications. The first section presents the overview of SMITM, followed by the aforementioned main procedures. The second section focuses on the system identification for a set of ambient vibrations of the Northampton Steel Bridge (NSB). The paper ends with few recommendations to improve the functionality of SMITM.

OVERVIEW OF SMITM

SMITM is a Matlab®-based system identification toolbox, that is suitable for estimating modal parameters of linear systems. While the program is capable of identifying any type of structure, the mode shape plot is optimized to show shear building structures and bridge systems. SMITM displays a GUI figure for welcome and each main procedure, including pre-processing, eigenvalue estimation, and post-processing. Additionally, there are two optional figures for larger views of the stabilization diagram and mode shapes after plotting those in the post-processing figure.

The welcome window prompts the user to choose either to load a previous identification result (.mat file), which is supposed to be created after eigenvalue estimation procedure, or to start a new session (Fig. 1). The pre-processing and eigenvalue estimation procedure is only conducted when the user starts a new session.

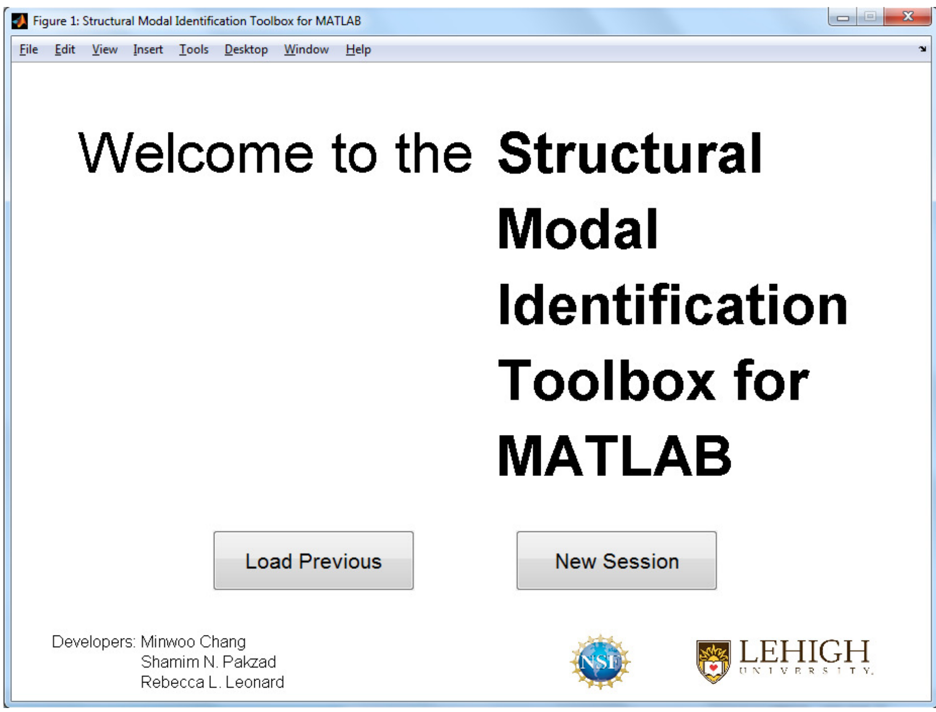

Fig. 1 Welcome figure for SMITM

Pre-processing procedure

The pre-processing figure is composed of six panels to assign the structural information and to perform signal processing. The panels are: 1) Data Type, 2) Geometric Information, 3) SI Method, 4) Sampling Frequency, 5) Filtering Options, and 6) Model Order Options.

The Data Type panel is where the user defines whether input/output or only output data is going to be utilized. Accordingly, the user needs to specify the data file (.dat) by clicking the *Get Output Data File* and the *Get Input Data File* pushbuttons (if it is activated). The Geometric Information panel has three radio buttons: 1) User-Defined, 2) Simple Shear Structure, and 3) Simple Bridge Structure. The User-Defined option requires specific geometric information, including node ordinate, connectivity between two nodes, sensor locations with a text format (.txt), and additional selection for the Response Direction. The SI Method panel has five options, depending on the data type: 1) ERA, 2) ERA-OKID, 3) ARX, 4) SRIM, and 5) N4SID for input/output system or 1) ERA-OKID, 2) ERA-NExT, 3) ERA-NExT-AVG. 4) AR, and 5) N4SID for the output only system. The Sampling Frequency panel allows the user to specify the sampling frequency and to inspect average of Power Spectral Density (PSD) at each node on the right portion by selecting Inspect PSD pushbutton. The Filtering Option panel shows three available filtering methods: 1) Fast Fourier Transform (FFT), 2) Butterworth, and 3) Chebyshev Type II. Depending on each method, the user needs to specify the filtering parameters as well. The Model Order Option panel is where the user assigns minimum, maximum, and increment of model order.

The user can start the eigenvalue estimation procedure by clicking the *Process* pushbutton on the bottom-right side of pre-processing figure.

Eigenvalue estimation procedure

Based on the information that the user defined in the pre-processing figure, the program starts the eigenvalue estimation procedure. The progress bar displayed on the screen helps the user monitor the model order on which the computing system is working. When the estimation procedure is completed, SMITM saves the identification results and structural information into the [eigen_estim_result.m], which can be used for the post-processing procedure.

See [13] for further information about the system identification methods in SMITM, such as fundamental theory and formulating the equivalent state matrix to the system.

Post-processing procedure

The post-processing figure is composed of four panels to investigate the results of identification and to determine modal parameters of a system: 1) Stabilization Parameters, 2) Stabilization Diagram, 3) Mode Shape Options, and 4) Mode Shapes.

The Stabilization Parameters panel is where the user defines the convergence bounds for parameters and the ranges of the x-axis. The *See plot* pushbutton shows the stabilization diagram based on the information defined in the Stabilization Parameters panel. A pushbutton in the upper-left corner, *Open a new window* pushbutton, shows a larger view of the stabilization diagram immediately, which allows the user to easily observe the result. The Mode Shape Options panel allows the user to decide between three options which modes will be plotted. The user needs to define an approximated frequency or model order in an editable box. If the user wants to plot specific modes, they should select a set of points from the stabilization diagram and export it to the workspace. The selected mode shapes appear after the user clicks one of pushbuttons on the Mode Shape Options panel. The user can observe mode shapes in larger window by selecting the *Open a new window* pushbutton and they may save modal parameters and computational time corresponding to that model order in a mat file [SIModal_Para.mat].

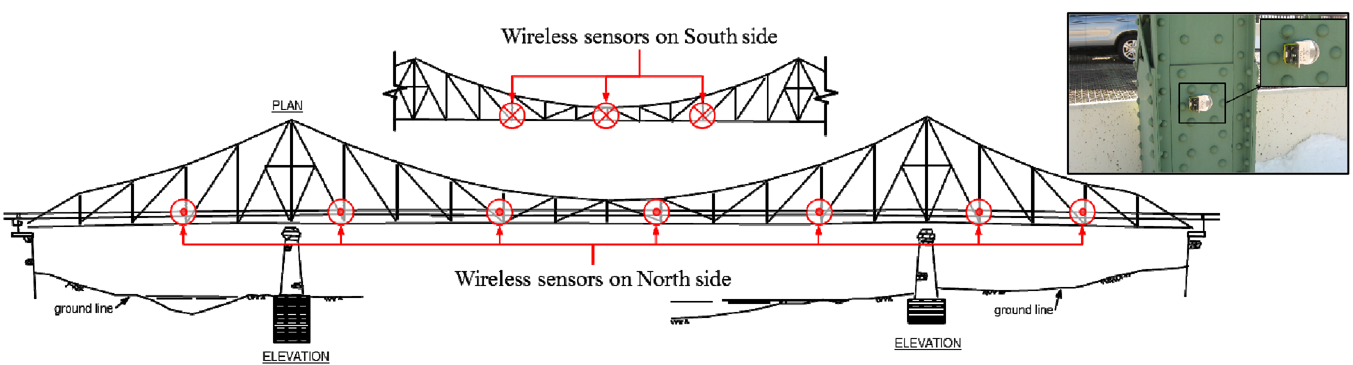

Fig. 2 Deployment of wireless sensors on NSB

SYSTEM IDENTIFICATION FOR NORTHAMPTON STEEL BRIDGE

The ambient vibration response was measured from the Northampton Steel Bridge (NSB) across the Delaware River, connecting Easton, Pennsylvania to Phillipsburg, New Jersey. The NSB is a cantilever truss bridge with a total span length of 550ft, supported by two piers. The WSN was formulated with 22 wireless sensors to measure ambient vibration response in vertical and transverse directions of the bridge. In this study, ten sensors were chosen to identify five vertical and two

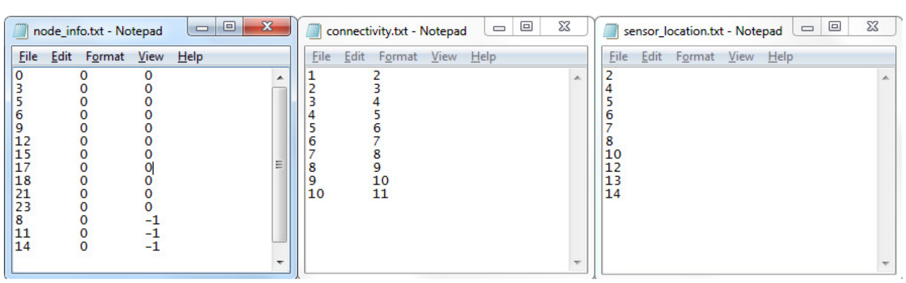

Fig. 3 Three text files [node_info.txt, connectivity.txt, sen_lo.txt] for geometric information of NSB

torsional modes. The deployment of sensors is shown in Fig. 2, where seven sensors, supposed to track mode shapes of the bridge, are mounted on the north side, and the other three sensors, supposed to distinguish the type of mode whether it is vertical or torsional, are mounted on the south side.

The Imote2, developed by Intel Co., is a processing board used to formulate the WSN by communicating with sensor board. The SHM-A sensor board, developed at University of Illinois Urbana-Champaign, is attached to the Imote2 and utilizes 3-axis Micro-Electro-Mechanical Systems (MEMS) to collect accelerations with the measuring range ±2 g. A TinyOS-based software package from the Illinois Structural Health Monitoring Project (ISHMP) was used to operate wireless sensors and to collect data efficiently [21].

The geometric information used in this identification is saved in three text files [node_info.txt, connectivity.txt, sen_lo.txt] as shown in Fig. 3. [node_info.txt] contains three dimensional geometric coordinates for all sensing nodes and supports. The node number is automatically recognized by counting the number of lines. [connectivity.txt] generates structural members by connecting two nodes, and [sen_lo.txt] indicates the node number where the sensors have been attached.

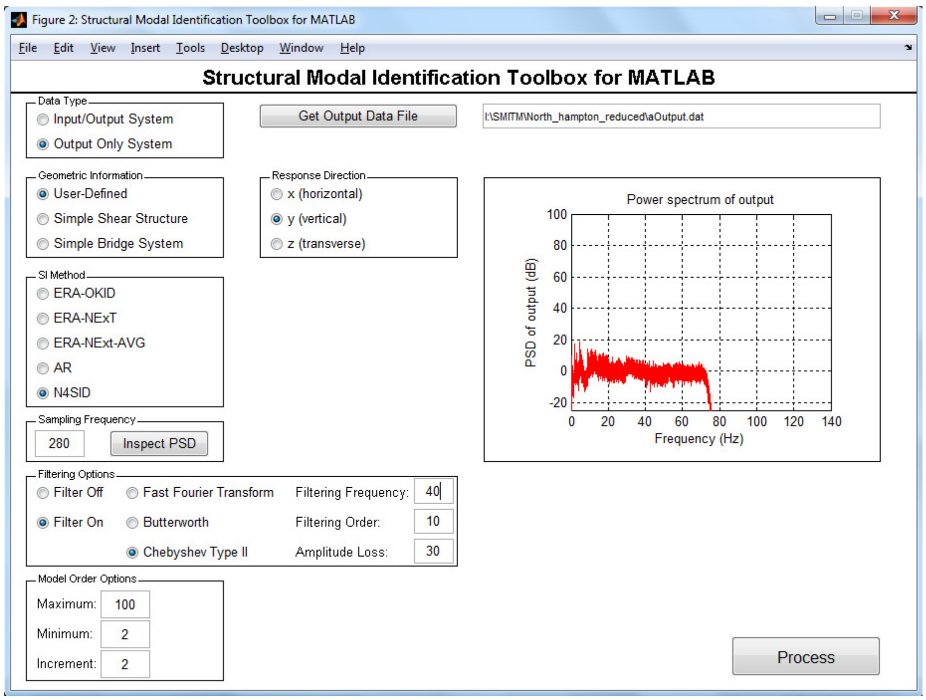

Fig. 4 Pre-processing figure of SMITM composed of six panels

After launching the SMITM in the Matlab® command window, the user needs to select *New session* pushbutton to start a new system identification. Fig. 4 shows the pre-processing figure to identify an output-only system, using ambient vibration data with specific geometric information. The response of the NSB is sampled down to 40 Hz by using Chebyshev Type II. Then, all five methods, including ERA-OKID, ERA-NExT, ERA-NExT-AVG, AR, and N4SID, are applied for even model orders between 2 and 100.

Fig. 5 is a post-processing figure, where the stabilization diagram and mode shapes are plotted based on the eigenvalue estimation result of N4SID. The convergence bounds for [natural frequency, damping ratio, MAC value] to plot a stabilization diagram are set to [0.1, 0.9, 0.2], respectively, and the frequency range up to 10 Hz is considered. The cohesion of identified modal parameters helps to determine the structural modes from computational noise.

There are eight distinguishable modes which are continuously converged when the model order increases. The mode shapes in Fig. 5 are plotted by selecting points one by one from the stabilization diagram. For each set of consistently identified parameters, a point from highest model order is chosen. The separate view of mode shapes can be plotted by selecting the *Open in new window* pushbutton, as shown in Fig. 6, where five vertical and two torsional modes are plotted. The eighth mode is difficult to distinguish due to the limited number of sensing nodes, which can be overcome by adding more sensing nodes.

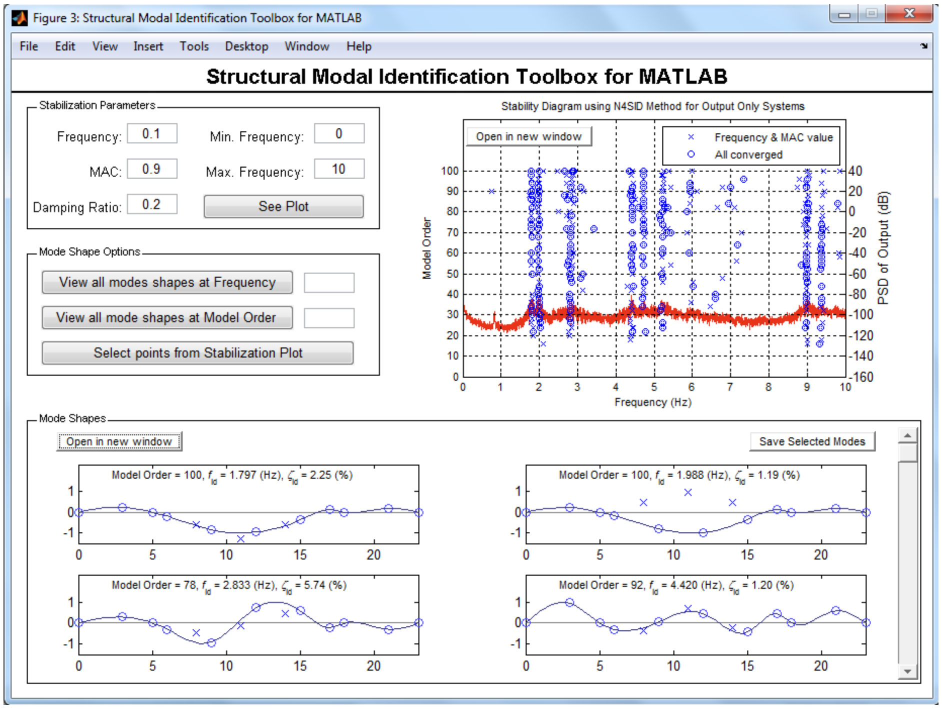

Fig. 5 Post-processing figure of SMITM composed of four panels

Table 1 shows the modal natural frequencies, damping ratios, and computational time to complete eigenvalue estimation for the corresponding model order from each identified mode. The modal damping ratios have shown differences up to nearly 50%, depending on the methods. However, the errors in modal natural frequencies are almost negligible. In order to investigate the efficiency of each method, the computational time to estimate modal parameters for a corresponding model order are recorded. Normally, ERA-NExT-AVG method takes least time while N4SID consumes an extremely large amount of time to complete eigenvalue estimation procedure, compared to other stochastic identification methods.

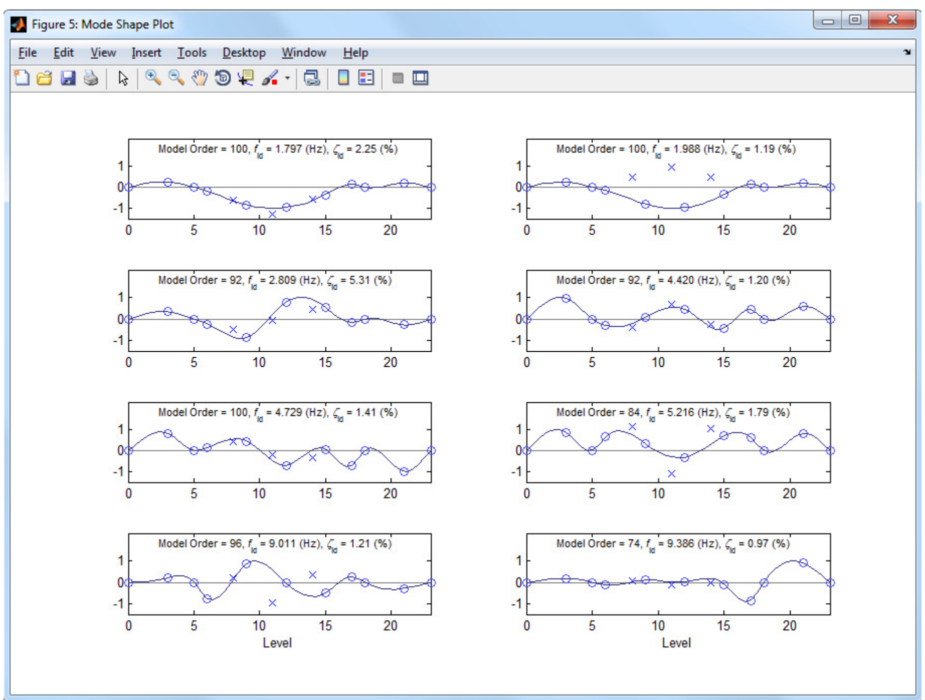

Fig. 6 Mode shape figures

CONCLUSION

The application study of SMITM is presented in this paper. Extensive testing of various system identification methods has shown that each method is capable of estimating modal parameters of a system. However, it requires considerable effort to obtain modal representation from structural responses. The toolbox software, SMITM, provides a convenient way to connect a gap between numeric models and experimental data. The GUI makes it easy to input required data and offers visual support to investigate the identification results. The result of the eigenvalue estimation procedure allows the user to plot a stabilization diagram and mode shapes without repeating the main computational tasks.

The example of the ambient vibration of NSB identified seven structural modes using ERA-OKID, ERA-NExT, ERA-NExT-AVG, AR, and N4SID methods. Based on this application study, SMITM is expected to provide useful results in estimating modal parameters for structural systems and health monitoring. In addition to the modal parameters, the program records the computational time to investigate efficiency of algorithm. SMITM, however, is currently in the development stage and is still being tested to uncover any programming bugs. SMITM developers are always open to improving the program's functionality and insert novel identification algorithms; users are encouraged to contact the developers with any suggestions.

Table 1 Identified modal parameters and computational time using ten sensing nodes on NSB

		ERA-OKID	ERA-NExT	ERA-NExT-AVG	AR	N4SID
1V	ω_{id} (Hz)	1.79	1.80	1.79	1.79	1.80
	ζ_{id} (%)	1.64	2.03	1.69	1.69	2.25
	t_{comp} (sec)	15.54	13.00	2.14	6.87	587.22
2V	ω_{id} (Hz)	2.82	2.83	2.86	2.83	2.81
	ζ_{id} (%)	5.74	5.13	6.61	5.37	5.31
	t_{comp} (sec)	13.08	10.85	0.68	5.24	497.79
3V	ω_{id} (Hz)	4.42	4.42	4.40	4.40	4.42
	ζ_{id} (%)	0.82	1.54	0.64	1.02	1.20
	t_{comp} (sec)	13.08	7.77	2.07	6.87	497.79
4V	ω_{id} (Hz)	4.74	4.74	4.73	4.72	4.73
	ζ_{id} (%)	1.59	1.14	1.32	1.34	1.41
	t_{comp} (sec)	15.54	13.00	2.14	6.13	587.22
5V	ω_{id} (Hz)	5.20	5.23	5.22	5.20	5.22
	ζ_{id} (%)	2.16	1.76	1.04	1.46	1.66
	t_{comp} (sec)	10.53	3.75	1.06	6.87	376.65
1T	ω_{id} (Hz)	1.98	1.98	1.99	1.98	1.99
	ζ_{id} (%)	0.87	1.20	1.09	0.87	1.19
	t_{comp} (sec)	15.54	11.79	2.14	6.87	587.22
2T	ω_{id} (Hz)	9.00	8.98	8.96	9.00	9.01
	ζ_{id} (%)	0.78	0.93	0.78	0.78	0.97
	t_{comp} (sec)	15.54	10.58	1.39	6.87	508.51

V = Vertical Mode, T = Torsional Mode

ω_{id}: Identified Modal Natural Frequency, ζ_{id}: Identified Modal Damping Ratio, t_{comp}: Computational Time

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