Graphical Interface Toolbox for Modal Analysis

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ABSTRACT: This paper introduces a new graphical user interface (GUI) based software toolbox for modal parameters (eigenfrequencies, damping ratios and mode shapes) identification. The toolbox is a MATLAB based software that implements several state-of-the-art techniques for modal analysis. Three frequency domain based techniques: the peak picking (PP) method, the frequency domain decomposition (FDD) method and the enhanced frequency domain decomposition (EFDD) method as well as two time domain based techniques: the Eigen realization algorithm (ERA) combined with the natural excitation technique (NExT) and stochastic subspace identification (SSI) method are adopted in the toolbox. Most of these techniques can be used for experimental (input-output data), operational (output-only data) and combined modal analysis of structures. The program inputs are raw measured data and if available, the excitation force. The toolbox offers extensive functionalities for the visualization and processing of the data, the determination and visualization of the structure’s modal parameters and comparison of the identified modal parameters. The program is compact, efficient and user friendly, making it very intuitive and easy to handle. This paper contains a detailed description of the various modal analysis capabilities of the toolbox, and runs through a sample application using the toolbox to extract modal parameters of a 3-story building model using experimental data.

1 INTRODUCTION
The identification of the dynamic characteristics of structures, such as the natural frequencies, mode shapes, and modal damping ratios, constitutes an essential step in the earthquake design of civil engineering structures [Farrar and James 1997]. Modal parameters of structures may be obtained both numerically and experimentally, and can be used in to check the construction quality, conduct damage assessment, and validate or improve analytical finite element structural models. While finite element analysis is widely used to model structural systems and estimate their modal parameters, creating accurate finite element models for complex structures is not an easy task due to difficulties in modelling micro cracks, material properties and boundary conditions. Modal testing can overcome these difficulties and lead to better predictions of the dynamic behaviour of the target structure. Moreover, vibration test results may be used to update and enhance numerical models of structure.

The System Identification Toolbox (SIT), introduced in this paper, is written in MATLAB [MATLAB 2010] language and is mainly used for identification of dynamic characteristics. In this toolbox, attention is focused on system identification techniques, which can deal with output-only measurements. The intention is to provide a user friendly toolbox for estimating modal parameters, make a comparison of five different system identification techniques, and compare modal parameters from different tests. It is widely understood that obtaining consistent modal parameters from different system identification techniques and from independent tests can significantly increase the confidence of identifying true modes. SIT contains several of the most widely used modal identification algorithms, allowing the user to analyze the data using more than one technique and compare the results directly. This modal identification capability is coupled with tools that allow the user to directly compare the identified modal parameters from independent dynamic tests. The program has been developed to be compact, efficient and user friendly.

An overview of SIT is provided, including an outline of each of the toolbox tabs. In each section, a snapshot of each tab is presented. Following the overview, an example of the application of SIT to
vibration data obtained from a 3-story building model is presented. This section contains a description of the test structure, data acquisition equipment, and testing procedure. It also contains a sample experimental modal analysis, complete with comparison of the identified modal parameters from the system identification techniques.

2 SYSTEM IDENTIFICATION TECHNIQUES

Three frequency domain based techniques and two time domain based techniques are adopted in the toolbox:

- the peak picking (PP) method [Bendat et al. 1993],
- the frequency domain decomposition (FDD) method [Brincker et al. 2000],
- the enhanced frequency domain decomposition (EFDD) method [Brincker et al. 2000, Jacobsen et al. 2007],
- the Eigen realization algorithm (ERA) [Juang and Pappa 1985] combined with the Natural Excitation Technique (NExT) [James et al. 1993],
- the stochastic subspace identification (SSI) method [Van Overschee and Moor 1996, Katayama 2005]. The two SSI based algorithms applied, SSI1 and SSI2, were both variations of stochastic subspace identification (SSI). In both methods the algorithm starts with system order of “SO” which is reduced by two with each iteration until the final iteration was run with a system order of two. Stable poles identified in each of these iterations were compared by one of two methods. In the first variation of SSI (SSI1), the stable poles identified around the singular values generated from the singular value decomposition of the power spectral density matrix [Brincker et al. 2000], were compared. If two consecutive poles within ±“SVD_dF” Hz of the singular value had change in frequencies within (Freq%), change in damping within “Damp%” and a modal assurance criteria (MAC) value greater than “MAC” user defined values, both poles were kept and averaged. If both poles did not meet these criteria the first pole was discarded and the second pole was compared to the subsequent one. This series of comparisons was continued until all stable poles in the frequency range had been compared and averaged. The resulting mode shape, natural frequency and damping are the combination of several stable poles and therefore provided a robust method of system identification. While the first method used singular values to identify stable poles, the second variation of SSI (SSI2) breaks up the entire frequency range tested into “SSI2_dF” Hz bands. Stable poles are compared within each band and averaged using the same method as the previous SSI1 variation. Those bands with the most stable poles are considered to contain true modes and are then used to compare to the other algorithms used.

The above techniques can be used for experimental (input-output data), operational (output-only data) and combined modal analysis of structures.

3 TOOLBOX DESCRIPTION

3.1 Test Parameters Tab

The first tab in the system identification toolbox is entitled “Test Parameters”, as shown in Figure 1. The top panel in this tab, “Data Manipulation and Visualisation”, includes functions for downloading the structural response measurements and calibration factors for the response data. Some tools in this tab such as “Decimate” and “Trim Data” can be used for reducing the size of large data sets. The “Trim Data” function offers a useful tool for choosing any desired section of the data in the time domain. It can also be used for choosing response data at some consecutive sensors from Ch1 to Ch2. The “Decimate” function reduces the original sampling rate for a sequence to a lower rate, the opposite of interpolation. The decimation process filters the input data with a low pass filter and then re-samples the resulting smoothed signal at a lower rate, reducing the sample rate of the input by a factor of \( r \). By default, decimate employs an eighth-order lowpass Chebyshev Type I filter with a cutoff frequency \( Fc \) of \( 0.8*(\text{Sampling Rate (Hz)}/2)/r \).
The time history response of any channel may be plotted in the top right graph entering the channel number and clicking the “Response” button. Four Butterworth filters: lowpass, bandpass, highpass, and bandstop are available in the “Filter” panel. Filter type, filter order and cutoff frequency can be defined in the same panel. The user can come back to the original unfiltered data at any time by simply choosing “None” in the filter type drop menu. Frequency domain functions Power Spectral Density (PSD), Fast Fourier Transform (FFT), Coherence, Cross Spectral Density (CSD), and Phase angle can be applied to the data using the “Plot Time Domain and Frequency Domain” panel. “Spectrogram” function returns the time-dependent Fourier transform for a sequence and displays this information as a spectrogram. The spectrogram is a view of the frequency content of the signal as a function of time.

In the second main panel in this tab, “System Identification”, the user can input the number of modes to be estimated and the system identification techniques to run for their particular test. The user also may change the default value of some parameters for the NExT/ERA and SSI techniques, such as Hankel matrix size, and user defined limits for finding stable modes. The user starts the analysis using the “Calculate Modal Parameters” button. The “Save Modal Data” button saves the modal data; frequencies, damping if available, and mode shapes in a single Excel file with multiple sheets. Independent data types from each system identification technique are saved in a separate sheet. “Clear Modal Data” removes modal data from the computer memory.

3.2 **Results Tab**

Once the analysis is complete, the identified modal parameters from each system identification technique can be shown and compared in the “Results” tab (Fig. 2). The identified natural frequencies are listed in the lower right table entitled “Natural Frequency”. If the geometry of the test structure is available, the user may select the “Input Structure Geometry” checkbox and then use the “Nodes Coord”, “Elements #” and “Sensors Loc” buttons to download the required geometry information. Nodal coordinate data include node number and x, y and z coordinates of each node. Elements data
include the element number and the node number at the element ends. Sensors location data includes
the sensor number, the corresponding node number and the sensor orientation. Structural geometry
data is used for better visualization of mode shapes. If the geometry data is not available, mode shapes
will be plotted by assuming the sensors are distributed evenly in a straight line. The “Plot Modal Data”
panel provides tools for plotting mode shapes for any specific system identification technique. The
“Modes” button simply plots the modal amplitude data for any particular mode as specified in the
“Mode #” edit box. The “Normalized Modes” option normalises modal amplitudes with respect to the
maximum modal amplitude value. For both “Modes” and “Normalized Modes”, modal amplitudes
values are also listed in a tabulated form.

Figure 2. “Results” tab

If the structural geometry was downloaded, the deformed structure will be plotted in thick green lines,
with the un-deformed structure shown in thin yellow lines. Mode shapes can be animated with the
frame per second “FPS”, number of cycles “No of cycles” and scale factor “Mode Shape Scale”
defined. “Hold On” button retains the current plot so that subsequent graphing commands add to the
existing graph. This feature is useful for conducting a visual comparison of mode shapes from
different techniques. In the lower right corner of “Results” tab, the correlation between mode shapes
can be estimated using the Modal Assurance Criterion (MAC) parameter [Ewins 2000]. The MAC is a
scalar quantity, and is a useful means of comparing two sets of mode shape data, even if the data is
complex. A MAC value close to unity suggests good correlation between modes and a value close to
zero indicates uncorrelated modes.

3.3 Compare Techniques Tab

The “Compare Techniques” tab offers some useful tools for comparing modal data from different
system identification methods. Comparative results may be plotted in figures as shown in Figure 3 or
listed in a tabulated form as shown in Figure 4. Before comparing modal data using “Plot Functions”
or “Show Tables” functions, modal data obtained from the different techniques must first be sorted.
Table 3. “Compare Techniques” tab

One of the system identification techniques must be chosen as a reference for sorting modal data using frequency values, as indicated in the “Baseline Method #” edit box. Frequency values from other techniques are sorted according to a frequency margin value specified in the “Frequency Margin (Hz)” edit box. For each mode in the baseline method, if no frequency value was found within the frequency margin for other techniques, the frequency value will be indicated as “NaN”. Sorted frequencies are listed in a tabulated format as shown in the upper left corner in Figure 3.

For any particular mode, four different plots will be displayed when the user clicks the “Plot Function” button. The first plot (upper left) shows the difference in frequency between each pair of system identification methods. Mode shape amplitudes from each method are plotted in the second plot (upper right). Similar to the difference in frequency graph, the third plot (lower left) shows the percentage difference in frequency between each pair of methods. MAC parameter for each pair of system identification methods is shown in the fourth plot (lower right). If desired, these values can be displayed in tabular form.

3.4 Compare Tests tab

The last tab in the toolbox entitled “Compare Tests” is similar to the “Compare Techniques” tab. Functions in this tab are the same as in the “Compare Techniques” tab, but these functions are used to compare modal parameters obtained from independent dynamic tests rather than comparing modal data from different system identification techniques. For any particular system identification method, modal data obtained from independent tests are compared in the same fashion illustrated in the previous section.

4 EXAMPLE APPLICATION: 3-STORY BUILDING MODEL

In order to test the functionality of the program, SIT was applied to experimental data from a 3-story
building model. The experiment was carried out by researchers from Los Alamos National Laboratory (LANL), [LANL 2003]. The test structure was constructed of aluminium columns and aluminium floor plates. The floors were 1.3 cm thick aluminium plates with two-bolt connections to brackets on the column. The base was a 3.8 cm thick aluminium plate. Support brackets for the columns were bolted to this plate. Dimensions of the test structure are summarised in Figures 5 and 6. Four air mount isolators, allowing the structure to move freely in the horizontal plane, were bolted to the bottom of the base plate. The isolators allowed the shaker to push and pull the structure without strong resistance and to provide more horizontal flexibility to the structure. A dynamic shaker was connected to a tapped hole at the mid-height of the base plate. The shaker was attached at corner D (shifted from the centreline of the base plate) as shown in Figure 6, so that both translational and torsional motions could be excited.

Figure 4. “Compare Tests” tab

4.1 Test setup and data acquisition

The structure was instrumented with 24 piezoelectric single axis accelerometers, two per joint as shown in Figure 6. This configuration allowed relative motion between the column and the floor to be detected. The nominal sensitivity of each accelerometer was 1 V/g. All input from the shaker to the base was random. In each test case, seven separate data sets were collected with the shaker input level at 2, 5 or 8 volts. Each time signal gathered consisted of 8192 points and were sampled at 1600 Hz.

4.2 Experimental modal analysis and comparison of modal data

The identified natural frequency values from the different system identification techniques are listed in a tabulated form in Figure 2. As clearly indicated in this table, the listed natural frequencies are not sorted. For example the second mode identified by SSI2 technique is similar to the first mode identified by all other techniques. Mode shapes were sorted with respect to the natural frequency
values from the PP method using a margin of 0.4 Hz utilizing the “Sort Modal Data” function in “Compare Techniques” tab. The maximum difference in the natural frequency value of the first mode is 0.3952 Hz as observed between the ERA and SSII methods (Fig. 4). The ERA was the least accurate of the techniques, for almost all the data sets and particularly for higher modes.

**Figure 5.** Basic dimensions of the 3 story frame structure

**Figure 6.** Floor layout as viewed from above

**Figure 7.** Mode shapes of the three storey structure using PP method

It should be noted that the identified modal data needs to be examined to distinguish between true modes and noise modes. In this study, three steps were used to account for this. Firstly, consistent results from different techniques and independent tests for any specific mode is strong evidence of true modes. Secondly, coherence function value between input force and each response would approach one at the natural frequencies corresponding to true modes. Thirdly, visual inspection of mode shapes identifies true modes and modes that are impossible given known structural constraints. The four
modes identified following this methodology, calculated by the PP method, are shown in Figure 7.

In order to investigate the influence of test repeatability on the identified modal parameters, four data sets were analysed. The first data set gathered with shaker input level at 2V, the second data at 5V and the third and fourth data sets obtained from two independent tests with shaker input level at 8V. By comparing the first four mode shapes from the four data sets using the MAC parameter, the following remarks were observed:

- All system identification techniques showed inconsistent results for the last data set.
- Very consistent results were observed for all modes obtained from PP, FDD and EFDD methods for the first three data sets.
- Consistent results were observed for all modes obtained from SSI1 and SSI2 methods for the first three data sets but with smaller MAC values than those found from PP, FDD and EFDD methods.
- No consistent results found from ERA in all modes.

5 CONCLUSIONS

A new toolbox of graphical-interface software algorithms, known as SIT, has been introduced and demonstrated. The toolbox is capable of performing experimental modal analysis using various system identification techniques, compare the extracted modal data from different techniques and compare modal data from independent dynamic tests. The three main functions of SIT have been proven effective through a case study of a 3-story building model and can easily be extended for use in other applications. The toolbox was successfully utilised for in situ dynamic characteristics identification of the decommissioned SH 20 Puhinui Stream Bridge in Manakau, New Zealand [Hogan et al, 2011].

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REFERENCES:


