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An Experimental Verification of the Eigensystem Realization Algorithm for Vibration Parameter Identification

Marlon D. Hill

Ph.D. Student, Civil & Environmental Engineering Department, Florida A&M University

Research Supervisor: Makola M. Abdullah, Professor

Summary

In recent years structural health monitoring (SHM) has become an important problem. One of the challenges in this new field is an accurate representation of structural properties by which the health of a structure can be judged. Modal analysis techniques are a common method used to determine these structural properties. One of the popular modal analysis techniques for civil structures is the eigensystem realization algorithm (ERA). This study provides an experimental verification of the ERA method. The verification was carried out using the shake table from the University Consortium on Instructional Shake Tables (UCIST) project. The experimental verification was based on several experimental test structures. The identified vibration parameters from the ERA were compared with the values based on classical structural dynamic theory and with frequency response values of the experimental models. The findings of this study will be used to gauge the accuracy of the ERA when used with the UCIST instructional shake table for implementation into a structural health monitoring program that, in the future, can be used to determine vibration parameters using models appropriate for classroom instruction.

Background

Structural health monitoring can be defined as the analysis of the dynamic behavior of civil structures to observe and examine the integrity of those structures. This area of study has lead to research involving parameter and damage identification. There are different levels of parameter and damage identification. Figure 1 illustrates the three stages of parameter identification of a civil structure. The research presented involves the first stage of parameter identification. A system of classification defining four levels can be applied to damage identification (Rytter 1993). They are determination that damage is present in the structure, determination of the geometric location of the damage, quantification of the severity of the damage, and prediction of the remaining service life of the structure.

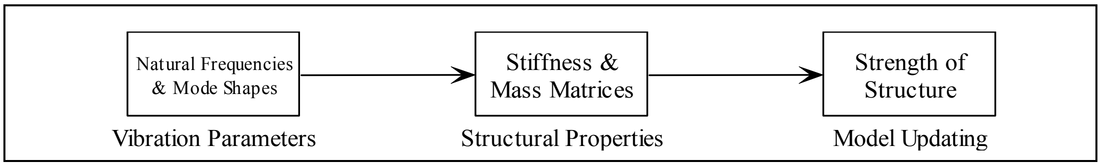

Figure 1. Stages of parameter identification

All civil structures require some form of routine maintenance. The purpose of this maintenance is to preserve structural integrity and prevent damage or failure. Visual inspection is still the predominant tool used to assess structural conditions. The main disadvantage of structural health monitoring (SHM) is its inability to classify invisible damage. Structural health monitoring has the potential to identify certain kinds of invisible damage.

The instructional shake table used to carry out the experimental procedure was provided by the University Consortium on Instructional Shake Tables (UCIST) (Dyke 1999). The UCIST Consortium consists of 23 member institutions associated with the earthquake research engineering centers; the Pacific Earthquake Engineering Research Center (PEER), the Mid America Earthquake Center (MAE), and the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The instructional shake tables were provided by the consortium (NSF Grant No. DUE-9950340) for the purpose of exposing emerging technologies and modern methods to reinforce theoretical concepts of structural dynamics through experimentation. Some objectives of the UCIST project are:

- To develop an understanding and an intuition regarding the dynamic nature of civil structures in undergraduate students.

- To provide non-engineering students with exposure to the potential consequences of earthquakes and to the dynamic behavior of civil structures.

- To provide exposure to emerging technologies and modern methods in seismic resistant design.

This article presents an experimental verification analysis of a modal analysis technique to determine the modal parameters of experimental test models for SHM purposes. Thus, eventually allowing the development of a comprehensive program based on the modal analysis theory that can be used to identify the dynamic properties structural models for use on the UCIST shake table. This research will be used to develop teaching modules for civil engineering students using the ERA method.

Literature Review

The traditional maintenance philosophy of civil structures utilizes schedule-based maintenance inspections. The in-service conditions of a structure are generally unknown; therefore, service manuals dictate the maintenance schedule. By incorporating SHM into the maintenance philosophy allows the maintenance and inspection procedures to be updated. This is known as performance-based maintenance. Incorporating SHM allows the service conditions to dictate the maintenance schedule.

Modal analysis is an important technique for SHM. Its fundamental application is to use modal testing methods to identify the vibration parameters of civil structures. There are numerous modal analysis testing methods. Here are a few of the available methods that can be used to identify the vibration parameters of a structure. The first is the Complex Exponential method (Maia, 1997). Most time domain parameter identification methods were derived from this method. It analyzes the free decay of the vibration responses in the time domain, as well as the other two methods. It is a simple method that is sensitive to noise. Next is the Ibrahim Time Domain method (Ibrahim, 1977). It uses the free vibration response of a structure to identify its vibration parameters. It is a vibration parameter identification method that is unable to provide system realizations. The method used for this research was the Eigensystem Realization Algorithm (ERA) (Juang, 1984). It is one of the most commonly used parameter identification methods. Not only is the ERA a vibration parameter identification method, it is also a system realization method.

Jer-Nan Juang and Richard Pappa developed the ERA in 1985. It is a modal parameter identification and model reduction algorithm of dynamic systems from test data. In addition, a minimum order realization technique, the ERA is an extension of the Ho-Kalman algorithm that incorporates singular value decomposition to counteract inherent noise.

Methodology

Sixteen experimental test structures were analyzed during these experiments. Aluminum and steel were the materials used to construct the test structures. Figures 2 and 3 shown below are of the test materials used to perform the experiments and the experimental test set-up, respectively. There were four 1-DOF experimental test structures used in this experiment. The test structures consisted of two aluminum and two steel models. The structures will be referred to using the following notation: *AL*15, *AL*20, *ST*15, & *ST*20. There were six 2-DOF test structures used in this experiment. Three aluminum, two steel, and one composite model with the following notations: *AL*15*AL*15, *AL*20*AL*20, & *AL*20*AL*15 and *ST*15*ST*15, *ST*20*AL*20, & *ST*20*ST*15. There were also six 3-DOF experimental test structures analyzed. The *AL*15*AL*15*AL*15, *AL*20*AL*20*AL*20, & *AL*20*AL*20*AL*15 and *ST*15*ST*15*ST*15, *ST*20*AL*20*AL*20, & *ST*20*ST*15*ST*15 were the designations used for the three aluminum, two steel, and one composite test structures respectively.

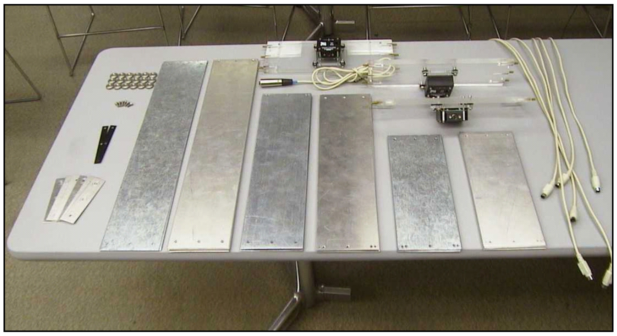

Figure 2. Experimental test materials.

Figure 3. Experimental set-up.

This was the experimental procedure undertaken to the identify the natural frequencies and mode shapes. The impulse force was exerted onto the test structure at random locations. The impulse response measurements were recorded and saved. There was a lag in the data. The lag was the time when the sensors started recording and the impulse was exerted. Figure 4 illustrates a typical impulse response from a test structure that includes the lag. To create the impulse response the lag was removed from the data sets. The experimental vibration parameters were obtained were obtained using the ERA method.

The theoretical and frequency response methods were used as verification tools to compare with the identified natural frequencies and mode shapes. For the theoretical method, the classical approach to structural dynamics was used to obtain the theoretical vibration parameters. The theoretical values were based on the material properties of the test structures. The frequency response natural frequencies were obtained by determining the peaks off the frequency response plots (FRP). The FRP for a 2-DOF test structure is shown below in Figure 5. The peaks of the FRP's correspond to the natural frequencies of the test structure.

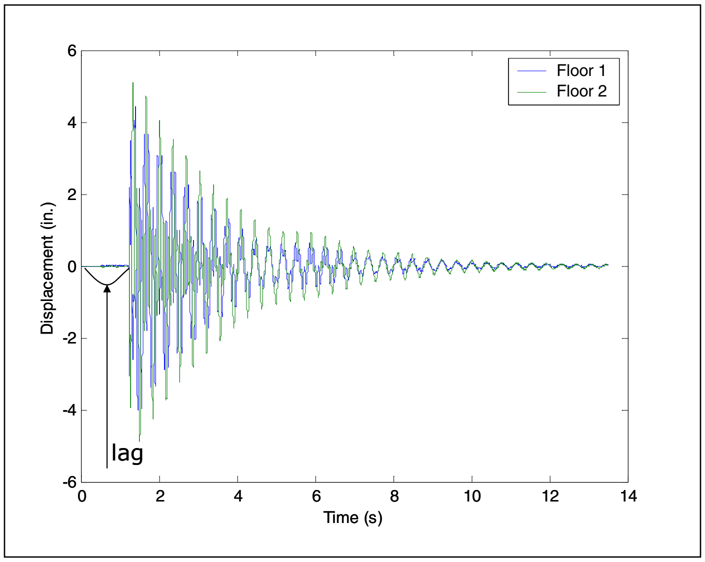

Figure 4. Impulse response with lag.

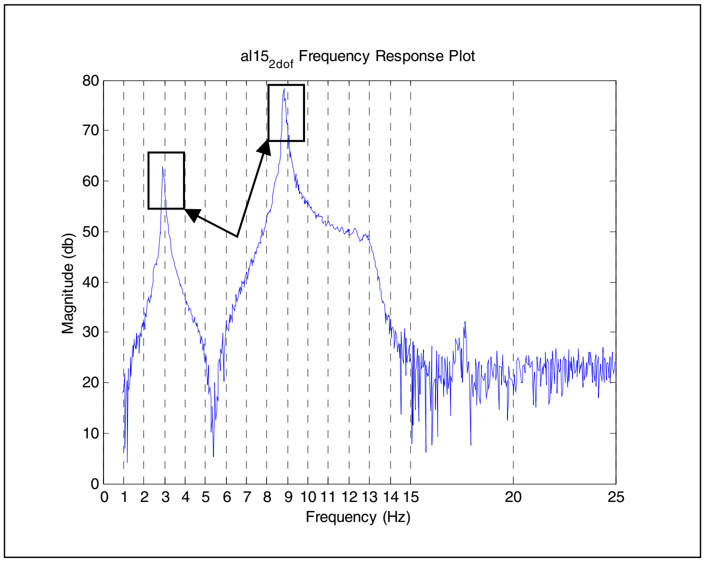

Figure 5. Frequency response plot of test structure.

Results

Tables 1 and 2, and Tables 3 and 4, contain the comparison data from the experiment. The ERA values were compared to the theoretical and frequency response values as a verification of the ERA method using the instructional shake table. Figures 6 and 7 contain the theoretical and ERA identified mode shape plots of the first and second mode respectively of a 2-DOF experimental test structure.

Table 1. Summary of results for ERA & theoretical values.

1DOF Natural Frequency Comparison $\left(\mathrm{rad}/\mathrm{s}\right)$			
Model	**ERA**	**Theoretical**	**% Difference**
AL_{15}	33.27	37.08	10.28
AL_{20}	21.49	23.28	7.67
ST_{15}	35.02	32.77	-6.86
ST_{20}	19.23	19.95	3.63

Table 2. Summary of results for ERA & frequency response values.

1DOF Natural Frequency Comparison $\left(\mathrm{rad}/\mathrm{s}\right)$			
Model	**ERA**	**Frequency Response**	**% Difference**
AL_{15}	33.27	33.55	0.84
AL_{20}	21.49	21.87	1.71
ST_{15}	35.02	36.95	5.22
ST_{20}	19.23	20.67	6.99

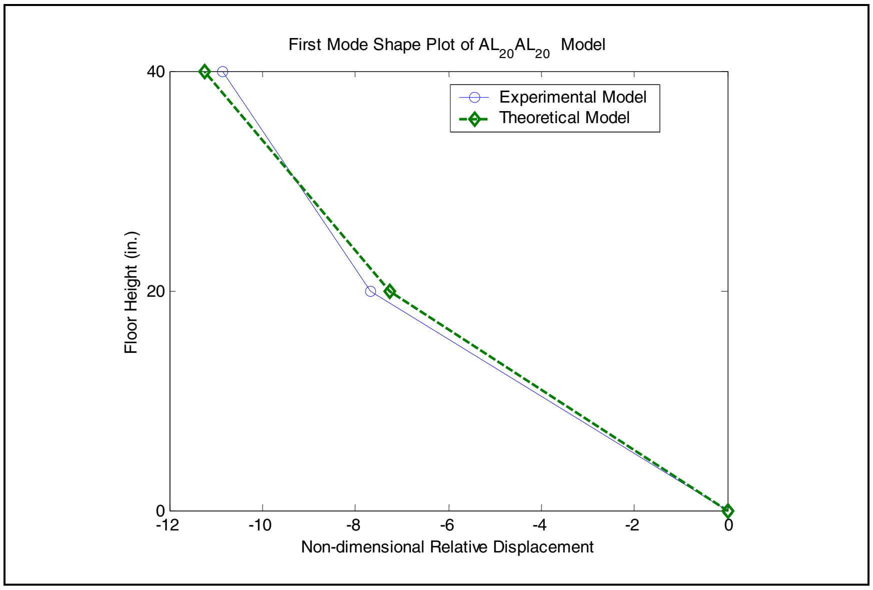

Figure 6. **Mode shapes for 2-DOF theoretical and experimental models.**

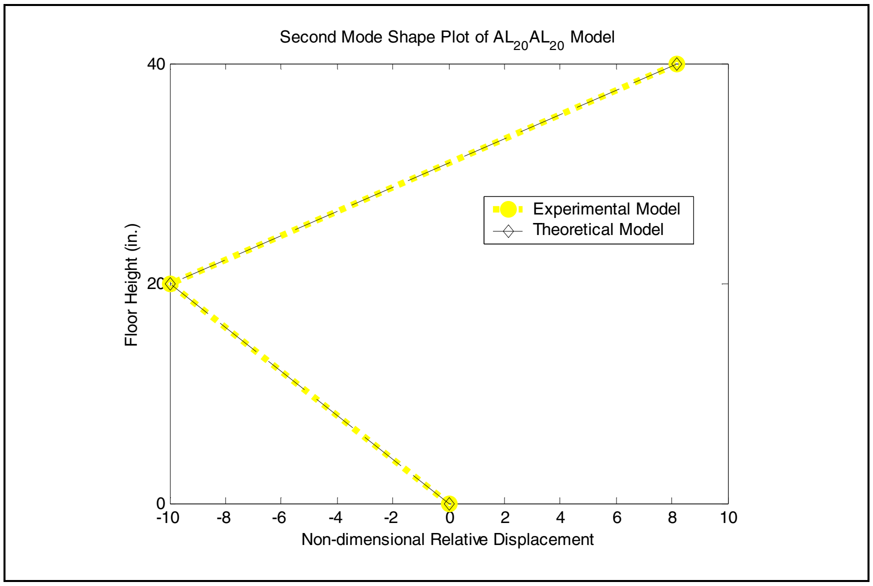

Figure 7. **Mode shapes for 2-DOF theoretical and experimental models.**

Table 3. Summary of results for ERA & theoretical values.

3DOF Natural Frequency Comparison $\left(\mathrm{rad}/\mathrm{s}\right)$

Model	ERA	Theoretical	% Difference
$AL_{15}AL_{15}AL_{15}$	12.97	15.12	14.23
	40.58	41.73	2.76
	62.95	58.93	1.82
$AL_{20}AL_{20}AL_{20}$	8.05	9.39	14.22
	25.15	25.86	2.72
	38.77	36.35	-6.65
$AL_{20}AL_{20}AL_{15}$	8.39	9.85	14.86
	28.60	29.24	2.21
	52.69	50.08	-5.21
$ST_{15}ST_{15}ST_{15}$	12.92	12.95	0.30
	42.11	35.58	-18.37
	63.79	49.65	-28.50
$ST_{20}AL_{20}AL_{20}$	8.22	9.21	12.45
	24.29	23.93	6.04
	37.96	35.29	-4.42
$ST_{20}ST_{15}ST_{15}$	8.27	9.85	16.03
	33.94	32.25	-5.27
	62.00	50.28	-23.31

Table 4. Summary of results for ERA & frequency response values.

3DOF Natural Frequency Comparison $\left({}^{\text{rad}}\!/_{\text{s}}\right)$

Model	ERA	Frequency Response	% Difference
$AL_{15}AL_{15}AL_{15}$	12.97	12.88	-0.66
	40.58	39.84	-1.86
	62.95	61.83	-1.84
$AL_{20}AL_{20}AL_{20}$	8.05	8.23	2.18
	25.15	25.64	1.88
	38.77	38.77	0.00
$AL_{20}AL_{20}AL_{15}$	8.39	8.48	1.09
	28.60	29.15	1.90
	52.69	53.09	0.76
$ST_{15}ST_{15}ST_{15}$	12.92	12.75	-1.26
	42.11	41.09	-2.48
	63.79	63.02	-1.23
$ST_{20}AL_{20}AL_{20}$	8.22	7.85	-4.63
	24.29	23.37	-3.93
	37.96	37.39	-1.54
$ST_{20}ST_{15}ST_{15}$	8.27	8.67	4.62
	33.94	35.19	3.53
	62.00	67.48	8.12

Conclusions

The ERA was effective in identifying the vibration parameters of the experimental test structures. The ERA and theoretical natural frequencies, ERA and frequency response natural frequencies, and ERA and theoretical mode shapes were in good agreement.

This experimental procedure can be used as an educational experiment. There are several benefits of using this research as an educational experiment. It can be easily reproduced and it can also provide hands-on experiments to develop an understanding of the concepts of SHM. It can also be used as a lab experiment and shared with other UCIST institutions. These are a few benefits of using this research as an educational experiment.

Future Work

Consideration of the effects of magnitude and location of the impulse force on the experimental test structures should be considered in future studies. Further work can also be done to compare the ERA with other modal analysis techniques to further gauge their accuracy against theoretical approximations of vibration parameters. In practice, it is nearly impossible to obtain an impulse response of a structure outright. Therefore, to use the ERA as an analysis tool for real structures the impulse response will need to be generated. Future studies can couple the ERA with the Natural

Excitation Technique (NExT), which uses ambient vibrations of a system to generate an impulse response of that system.

Acknowledgements

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