A Remotely-controllable Shaking Table for Web-based Structural Testing under Earthquake Loading

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Abstract

A web-accessible shaking table experiment is presented as a means for students and researchers to remotely control and monitor the behavior of a test structure due to vibratory excitations. Implemented at MIT’s Civil Engineering Department, and sponsored by the iLab initiative of Microsoft’s iCampus Project, the Shake Table WebLab serves as an educationally-oriented online space for real-time experimentation. Facilitated accessibility, safe operation and expandability are essential challenges at the root of the design and implementation of the Shake Table WebLab. Two main characteristics of the developed web-based system are interactivity, provided through synchronized control/response processes, and sensor-based monitoring of the experiment, which is essential for real-time interactivity. Throughout the paper, we will state the goal of the project, a description of the implemented technologies and system components, and computational methods which are programmatically applied in order to predict structural responses due to various seismic loading.

Introduction

Providing accessibility to the shaker table apparatus through the web has been advocated by academic and research interests to facilitate efforts of understating vibratory effects on a structure. The internet serves as an easily accessible medium for students to perform their experiments. The developed web application is configured so as to eliminate possibilities of human error in activating the shaker table. Such errors may lead to operation under unsafe conditions and therefore jeopardize the lab setup and anyone near it. Thus necessary precautions are carried out programmatically through accessibility processes that automatically execute whenever a web user conducts an experiment.

The fully functional system (http://flagpole.mit.edu:8000/shaketable) allows web-users to excite a two-story structure, which is three feet high, by vibrating its base while receiving accelerometer readings from three different levels as the experiment proceeds. Registered users may upload their own input data, such as the seismic ground accelerations of a newly occurring earthquake, and therefore study the corresponding behavior of a real structure. An already developed tool utilizes frequency domain transfer functions to compare the measured structural response at the upper levels with a predictable result based on seismic vibrations applied to the structure’s base (Caicedo at al).

System Architecture

The shaker table used is a product of Quanser Consulting Inc. and the system is built on the Microsoft .Net Framework (Prosise, 2002) through server-hosted Active Server Pages
and browser-embedded Windows Form Controls. Web Service methods are implemented for remotely initiating processes that control the shaker table.

*Initial System Conditions*

The uniaxial servo-controlled electromechanical earthquake simulation system consists of the following components: an 18”x18” shake table, a power module equipped with a microcontroller-based safety circuit to drive the table, a data acquisition board to drive the power amplifier and collect sensor responses, and a two-floor test structure (Quanser Consulting). The assembled three-foot tall structure carries one accelerometer on each floor. The shake table is accompanied by WinCon, a client/server computer application which control the shaker. Since the aim of the project transcends the capabilities of WinCon and aims at facilitating accessibility to the lab, a user friendly client-side web application is needed. This application relies on WinCon as an intermediary for controlling/monitoring the shake table setup.

*Extended System Architecture*

The newly developed system architecture is based on three main components: a control server, a web/database server and web-clients. The control server is a dedicated computer that has direct access and control of the shake table setup. Software hosted on the control server include WinCon 3.2 to interface with a data acquisition/controller board, Matlab as a data processing environment, and a Web Service hosted in Internet Information Services (IIS) and serves to trigger server-side processes initiated by a client application. The Web Service translates client requests, carried out through the web application, into corresponding activities on the control server. For instance, a user request to start an experiment executes a web method which checks the status of the control server and calibrates the shake table before initiating the experiment. The web/database server is another computer that hosts an ASP .Net web application as well as an SQL Server database. Users access the shaker table through the website hosted on the latter server computer. A client is representative of a web user accessing the lab through an internet browser. The web application entails a Windows Form Control embedded within a web page to provide a rich control and plotting interface to the lab. When an experiment is started, the client application establishes a direct TCP socket connection to stream data to and from the control server.

There are three main types of activities that a user may conduct online. The first type of experiment entails choosing one of a list of previously-loaded table excitations. Two lists of experiments are provided: a public list accessible by the whole user community and a private list consisting of experiments that are created by the logged-in user. Second, a user may create a new experiment by uploading an acceleration-based data file to the server. Server-side processes automatically handle appropriate scaling and filtering of raw data to insure compatibility with the capabilities of the shaker table. The third type of experiment is more interactive in the sense that a user alters a sine-wave input signal to be applied to the shaker as sensor responses are simultaneously streamed back and plotted within the user’s internet browser.
Users access the lab through an internet browser which is compatible with Microsoft’s .Net Framework such as Internet Explorer. The client application is expandable in terms of the data processing tools that might be added depending on the purpose of the user. The common experiment interface shown in Figure 1 provides the following features:

- Real-time plotting of measured acceleration responses
- Fast Fourier spectra dynamically updated as the experiment proceeds
- Transfer function spectra and the extraction of dominant frequencies (computational means for finding transfer functions are elaborated in the next section)
- Capability to save plots to data files
- Simultaneous plotting of actual and predicted responses in variant line colors
- Capability to export transfer functions to file and reapply them to several experiments
- A live video display of the shaker table

An essential feature of a remotely controllable shake table is authorizing user accessibility and managing simultaneous user requests to activate the shaker. Accordingly, these concerns are handled by a user-account management database with various permission levels and a queuing mechanism implemented on the control server. The implemented queueing technique provides lab access to a single user at a time and on a first-come-first-serve basis.
Computation of Transfer Functions

In order to determine the transfer functions from ground accelerations to each of the upper floor accelerations, a digital filter is required to transform input acceleration signals at the base into a response signal at an upper floor. Figure 2 is a snapshot of transfer functions plotted after running a sine-wave interactive experiment.

Figure 2. Transfer function tab view of a sine-wave experiment displaying frequency peaks (1.4 and 5.2 Hz).

In identifying an appropriate digital filter, we look for a causal filter approach whereby values of \( y \) are not dependant on future values of \( x \). Moreover, since we are dealing with infinite time histories of acceleration, the filter which is to be implemented must have an infinite sum. Accordingly, an Auto-Regressive Moving Average (ARMA) model is used to represent an Infinite Impulse Response Filter (IIF) as such:

\[
\sum_{k=0}^{M} a_k y_{n-k} = \sum_{k=0}^{N} b_k x_{n-k}
\]

\[
y_n = \sum_{k=0}^{M} b_k x_{n-k} - \sum_{k=1}^{N} a_k y_{n-k}
\]

where \( a \) and \( b \) are sequences with lengths \( M \) and \( N \) respectively, and the coefficient \( a_0 \) is normalized as 1.
In expanding the last equation, values for x and y with subscripts less than zero are considered as zero. In matrix form, the last equation is written as:

\[
\begin{bmatrix}
y_0 \\
y_1 \\
y_2 \\
\vdots \\
y_p
\end{bmatrix} =
\begin{bmatrix}
x_0 & 0 & \cdots & 0 \\
x_1 & x_0 & \cdots & 0 \\
x_2 & x_1 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
x_p & x_{p-1} & \cdots & x_{p-M}
\end{bmatrix}
\begin{bmatrix}
x_0 \\
x_1 \\
x_2 \\
\vdots \\
x_M \\
x_{M+1} \\
\vdots \\
x_{M-1} \\
x_M \\
x_{M-2} \\
\vdots \\
x_1 \\
x_0
\end{bmatrix}
\begin{bmatrix}
y_0 \\
y_1 \\
y_2 \\
\vdots \\
y_N \\
y_{N-1} \\
\vdots \\
y_{N-2} \\
y_{N-3} \\
y_0
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0
\end{bmatrix}
\begin{bmatrix}
y_0 \\
y_1 \\
y_2 \\
\vdots \\
y_N \\
y_{N-1} \\
\vdots \\
y_{N-2} \\
y_{N-3} \\
y_0
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
0 \\
\vdots \\
0 \\
0 \\
\vdots \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2 \\
\vdots \\
a_M \\
b_0 \\
b_1 \\
\vdots \\
b_M
\end{bmatrix}
\]

more compactly:

\[ y = Xb - Ya \quad \text{or} \quad y = Wc \]

where:

\[ W = [X - Y] \quad \text{and} \quad c = \begin{bmatrix} a^T \\ b^T \end{bmatrix} \]

This system of equations is over-determinate because it has more rows (P) than unknown variables (M+N+1). Therefore, the least-squares method is adopted for a solution by multiplying each side of the equation by the transposed matrix:

\[ W^T y = W^T W c \]

\[ c = [W^T W]^{-1} W^T y \]

The transfer function to be found can be represented by the coefficients of vector c which in turn is reliant on the matrices X and Y. However, the matrix expansion contains inaccuracies which result from the fact that the initial boundary values entail missing numbers which have been replaced by zeroes. A more accurate calculation of the vector c would therefore be based on modified matrices, X’ and Y’, instead of X and Y. The modification entails disregarding initial rows in the matrices which contain missing values. The disregarded rows are enclosed in dashed boundaries in the previous matrix representation.

Accordingly, by finding c, vectors a and b which characterize the digital filter are determined. Having determined the system which relates the output values y to input values x by using known values for x and y, we can therefore apply the resulting filter to predict the response due to any other input signal x. The peak frequencies of the system can be extracted by obtaining the transfer function. This is done by writing the recursion equation in the frequency domain (refer to Figure 3). The poles of the transfer function
are obtained by finding the roots of polynomial A in the denominator of H(w).

\[ A(\omega)Y(\omega) = B(\omega)X(\omega) \]
\[ Y(\omega) = \frac{B(\omega)}{A(\omega)} X(\omega) = H(\omega).X(\omega) \]

where X, Y, A and B are the Fourier transform complex vectors of \( x(t), y(t), a \) and \( b \) respectively. FFT computations are adopted from Numerical Recipes algorithms (Press et al, 2002).

[Diagram showing the transfer functions]

**Figure 3. Frequency-domain representation of transfer functions.**

**Conclusion**

This paper presented an overview of a web-accessible shaker table experiment. The implemented system is designed with an easily expandable architecture in order to enable future researchers to add functionalities that suit their fields of interest. Relevant fields of study include experimenting with real-time signal processing algorithms and filtering techniques that provide further information acquired from sensor readings. Such techniques help in understanding the behavior of structural models and provide insight on means to minimize encountered damage in large-scale structures.

**Acknowledgements**

We would like to thank Microsoft Cooperation for providing the necessary funds for the project through the iCampus alliance with MIT. Thanks to the iLab team for their continuous interest in and appreciation of the Shake Table Weblab. Quanser Consulting Inc. has also been very cooperative in sorting out technical problems throughout the course of the project.

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