

Virtual Laboratory for Experimental Structural Dynamics

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Abstract

This paper presents a Java-Powered Virtual Laboratories (VL) which has been developed to provide a means for on-line interactive structural dynamics experiments for undergraduate and graduate education. This VL intends to provide a conceptual and practical understanding of a wide range of topics related to the collection, analysis, and interpretation of data from dynamic testing, including sensor type and placement, aliasing, windowing, nonlinearities, etc. A multi-story shear building is employed as a test bed and the responses of the structure are obtained through the linear/nonlinear dynamic analysis. The VL is available on-line at <http://sstl.cee.uiuc.edu/java/esd/VirtualLab.html>. This paper presents the unique features and usage of this VL.

Keywords: virtual laboratory; earthquake engineering; nonlinear dynamic analysis; experimental structural dynamics

1. Introduction

Hands-on experiments are one of the best ways to teach students about the dynamic behavior of structures. However, the setup for dynamic testing is costly and therefore typically not available or practical to be employed by most instructors. Moreover, because of the expense and lack of repeatability of testing structures in the nonlinear range (i.e., undergoing damage), nonlinear dynamic behavior is challenging to study in the laboratory. These difficulties can be overcome by an alternative such as an appropriately designed simulation tool. For this purpose, a series of VLs have been developed (Gao et al. 2005). The Structural Control VL allows users to compare the

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effect of using two different control systems to reduce the structural response of a structure subjected to earthquake excitation. The Linear and Nonlinear Base Isolation VL facilitates a better understanding of the benefits and limitations of using isolation for seismic hazard mitigation. The Nonlinear Dynamics VL allows students or practitioners to better understand the effect of the nonlinear behavior of buildings. The Java programming language has been employed to build the VLs so that the VLs can make use of the unique advantages of Java. The VLs can be accessed through the internet so that users only need to open the website without any installation procedure. Maintenance is manageable, as the latest version of VL is always downloaded when users connect to the VL website. Platform independency of the VLs allows users to run the VLs regardless of the operating system they use. In addition, any number of students can run the VL simultaneously due to the VLs being executed on the user's local computer. These VLs have been published on the website of the Smart Structures Technology Laboratory (SSTL) of the University of Illinois at Urbana-Champaign (<http://sstl.cee.illinois.edu/education.html>).

This paper reports on a newly developed VL that is intended to provide a conceptual and practical understanding of a wide range of topics related to the collection, analysis, and interpretation of data from dynamic testing. Following a technical summary, the VL is overviewed, and examples its unique educational features are provided.

2. Technical Summary

The purpose of this VL is to illustrate various issues important to experimental dynamic testing. This VL utilizes a multi-story shear building model as a test bed and provides essential features of the experiment such as sensors type and placement, data acquisition, aliasing, windowing, nonlinearities, etc. With the user-defined parameters for the virtual experiment, the VL calculates responses of a structure through linear/nonlinear dynamics analysis, and the measured responses are processed to obtain the characteristics of the structure in the frequency domain. Results from these analyses give users a unique insight into the dynamic behavior of the structure from the experimental point of view.

2.1 Data acquisition

Data acquisition, one of the primary parts of an experiment, is simulated in the VL, including sensors, observation noise, and time discretization. Users are allowed to specify the locations and types of sensors. Six types of sensors are available to measure displacement, velocity, acceleration, spring force, damping force, or shear force. Similar to the laboratory environment,

the total number of sensors is limited; to prevent excessive computational time or use of memory, up to eight sensors can be employed. The measurement noise, which is inevitable in an experiment, is also simulated. The VL allows the users to adjust the noise levels in the measured ground excitation and measured responses from 0% to 5%. Anti-aliasing filters are simulated in the VL. Aliasing is associated with the sampled data and occurs whenever the data contains frequency components larger than the Nyquist frequency (half of the sampling frequency). Without use of appropriate anti-aliasing filters, the measured data would be severely and unrecoverably distorted. An 8-pole elliptic anti-aliasing filter is implemented in the VL.

2.2 Data processing

The measured data is then processed to extract the dynamic characteristics of the test structure using the Fast Fourier transform (FFT) calculation. The measured response of the structure is divided into segments of data (windows) with the lengths equal the number of the FFT. The measurement time is determined by the number of averages and FFT points, the sampling time, and overlap between windows. Since finite data lengths always result in spectral leakage, windowing is usually employed to minimize the impact on the processed data. The VL supports 3 kinds of windows: Boxcar, Hanning, and Hamming. Using the FFT of the data, the VL computes the power and cross spectral density (PSD and CSD, respectively), transfer function, auto and cross correlation, coherence function, and impulse response function.

2.3 Structural model and computational method

Four models for the structure's stiffness and damping are considered, including linear stiffness and linear viscous damping; linear stiffness and nonlinear power-law damping; hysteretic stiffness using the Bouc-Wen model and linear viscous damping; and hysteretic bilinear stiffness and linear viscous damping. These nonlinear models illustrate users how nonlinearity of the structure affects the measured dynamic characteristics. The dynamic problems associated with the linear and nonlinear models are solved by numerical integration algorithms. The Generalized α -method is utilized to solve the hysteretic bilinear stiffness problem, and the Runge-Kutta method is applied to handle all other linear and nonlinear analysis (Tedesco et al., 1998; Belytschko and Hughes, 1983; Berg, 1989) and the anti-aliasing filter.

2.4 Flow of virtual experiment

Fig. 1 shows the computation procedure of the VL. First, the selected ground excitation is filtered so that the frequency ranges from zero to the cutoff frequency if necessary. Among the provided ground motions, only white noise and historical earthquake records are filtered to ensure they are band-limited. Imposing the filtered excitation as an input of the system, the

output is calculated using the Runge-Kutta method. The output at the sensor location and ground excitation are filtered to suppress aliasing. Measured inputs and outputs are then processed to obtain spectral characteristics with user-defined parameters such as the number of FFT points and the type of windowing. Measured responses and estimated spectral functions are then ready to be displayed for the user.

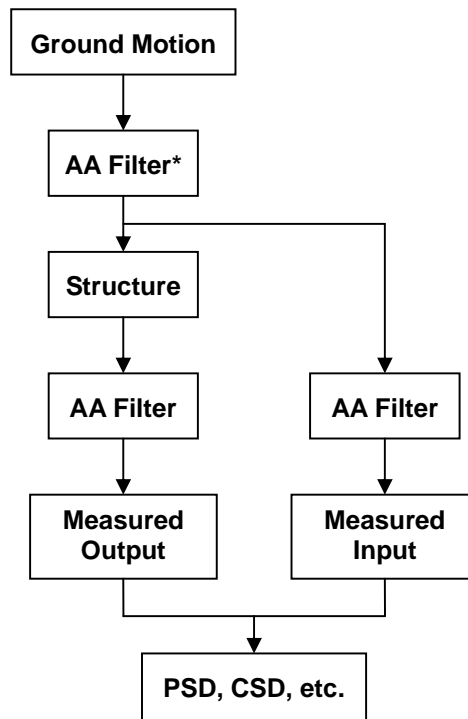


Fig. 1 Flow chart of computation (*AA filter is not used for some excitations)

3. Overview of Virtual Laboratory

A wide variety of the essential aspects of a dynamic experiment are illustrated in the VL. Users can specify their own structure by changing the number of stories, mass, stiffness, damping and nonlinear properties. In addition, the type of excitation and location of sensors can be selected, and parameters related to data processing are also provided. When the user clicks the “Calculate” button after defining parameters, the VL conducts the virtual experiment on the linear and nonlinear models of the multi-story building and computes the various spectral estimates such as PSD, CSD, transfer function, etc. using the measured responses at the sensor locations. Once the computation is finished, users can view the animation of the structure as well as the measured dynamic responses and spectral function estimates.

The user interface of the VL shown in Fig. 2 consists of a control panel, an animation panel and four plot panels. The animation panel located in the middle shows the structure used in the virtual experiment animating when the “Animation” button is clicked. The control panel on the right side is used to specify various parameters for the structure, ground excitation, sensor, and data processing. This panel also contains useful buttons for computation, animation, help, etc.

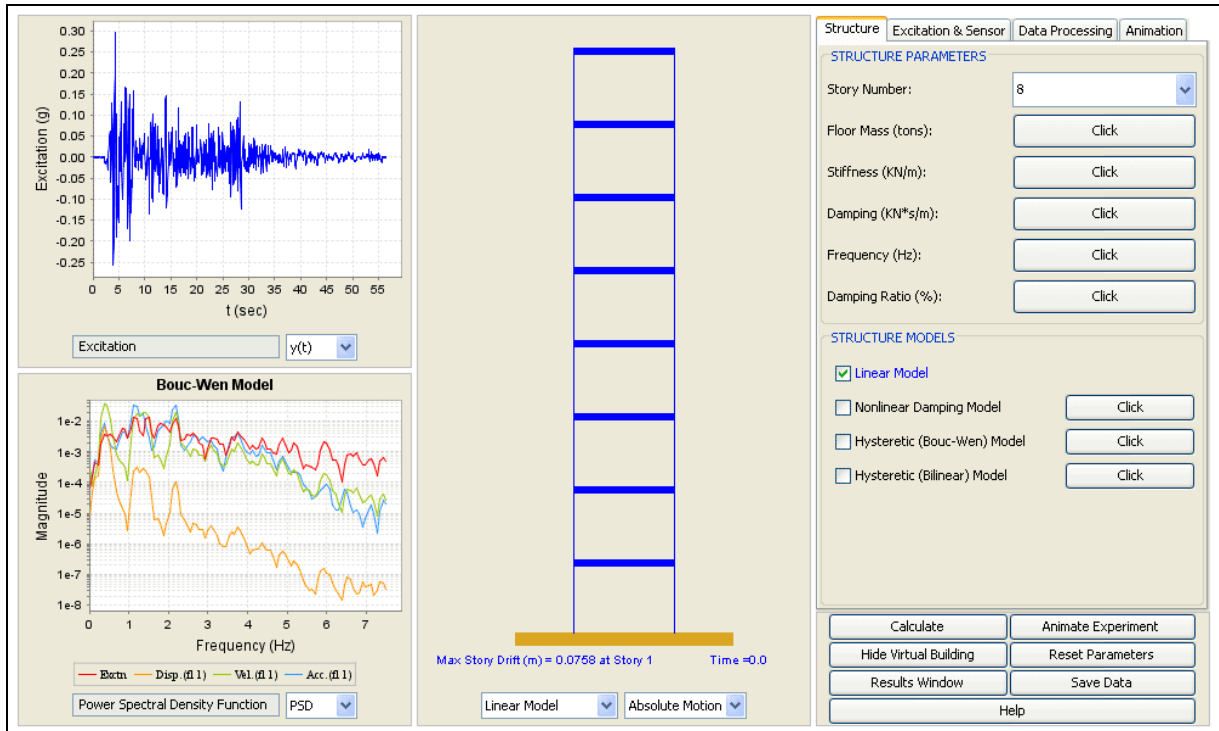


Fig. 2 Experimental Structural Dynamics Virtual Laboratory

Parameters provided in the control panel are as follows:

Structure tab

- Story Number: Total number of stories. (The default is 8.)
- Floor Mass: Mass of each floor. Clicking the button, a dialogue box shown in Fig. 3 will pop up, in which users can specify the mass of each floor. (The default mass of each floor is 8 tons.)
- Stiffness: Linear stiffness for each story. (The default is 2000 kN/m.)
- Damping: Viscous damping coefficient for each story. (The default is 10 kN·s/m.)
- Frequency: Natural frequency associated with the structural parameters. These values will be updated automatically if structural parameters are changed.
- Damping Ratio: Damping ratio associated with the structural parameters. These values

will be updated automatically if structural parameters are changed.

- Structural Models: Checking one or more boxes leads to display corresponding responses on the plot panel.
- Involution Coefficient: Parameters associated with the nonlinear damping model. By clicking the button at the right side of the Nonlinear Damping Model, a dialogue box will be opened allowing users to change these coefficients. The default is 0.5.
- Yield Displacement and Post-yield Stiffness: These parameters are used in the Bouc-Wen model and bilinear model. The defaults values are 0.02m and 1000KN/m, respectively.

Excitation and Sensor tab

- Excitation: This drop-down menu allows users to select a ground excitation among band-limited white noise, impulse, sinusoidal, chirp, as well as 4 historical earthquake excitations. The default excitation is the N-S component of the 1940 El-Centro earthquake.
- Time Step: Time step of the ground excitation. This value for the historical earthquake data is 0.02sec. Otherwise, the time step is 1/4 of the sampling time.
- Sensor Type and Location: Clicking the button, a dialogue box shown in Fig. 4 will pop up, in which users can change the locations and types of the sensors. Total number of sensors is limited as it is in real experiments. Furthermore, it also prevents the large number of sensors from causing Out-of-memory problem. The maximum number of sensors is 8.

Data Processing tab

- AA Filter: Users can choose to turn the anti-aliasing filters on or off. The frequency-dependent functions are shown up to the cutoff frequency (i.e., $1/1.28 * \text{Nyquist frequency}$) when the filter is used. Changing this option will immediately affect the plot panels. By turning off the AA filter, the unfiltered excitation or responses will be used to plot within the range between 0 Hz to the Nyquist frequency.
- Cutoff Frequency: Cutoff frequency of the AA filter. Since the sampling time is related to the cutoff frequency, users may want to change the cutoff frequency to select other values of sampling time. (The default value is 7.5Hz.)
- Sampling Time: Sampling time step. This value is 2.56 times of the cutoff frequency and will be automatically updated if the cutoff frequency of the AA filters changes. Even though the AA filter is turned off, the sampling time is determined by the cutoff frequency of the AA filter.
- # of FFT: Number of data points in the FFT calculation. (The default value is 256.)

- # of Averages: Number of the averages used in the calculation of the PSDs, CSDs, and transfer functions. The total simulation times for non-earthquake excitations are determined by overlap, the number of FFT points and averages. Thus, this option is not available for earthquake data since durations of them are already decided. A large number of FFT points or averages results in long simulation times. (The default value is 5.)
- Overlap: Portion of the overlap used in the calculation of the auto and cross spectral density functions. Since windowing discards the relevant information at the beginning and the end of the data, overlapping is introduced to reduce the variance of the resulting spectral estimates. (The default value is 50 %.)
- Windowing: Windows used in the FFT calculation. To minimize the spectral leakage, it is common to use a time window that eliminates the discontinuities at the beginning and end of a time history. Three windows are provided: Hanning, Hamming, and Boxcar.

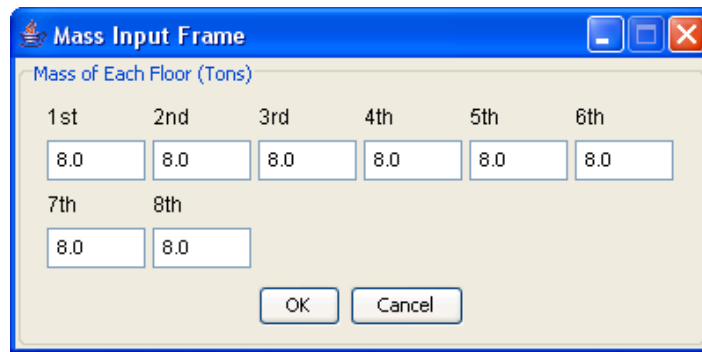


Fig. 3 Mass Input dialog box.

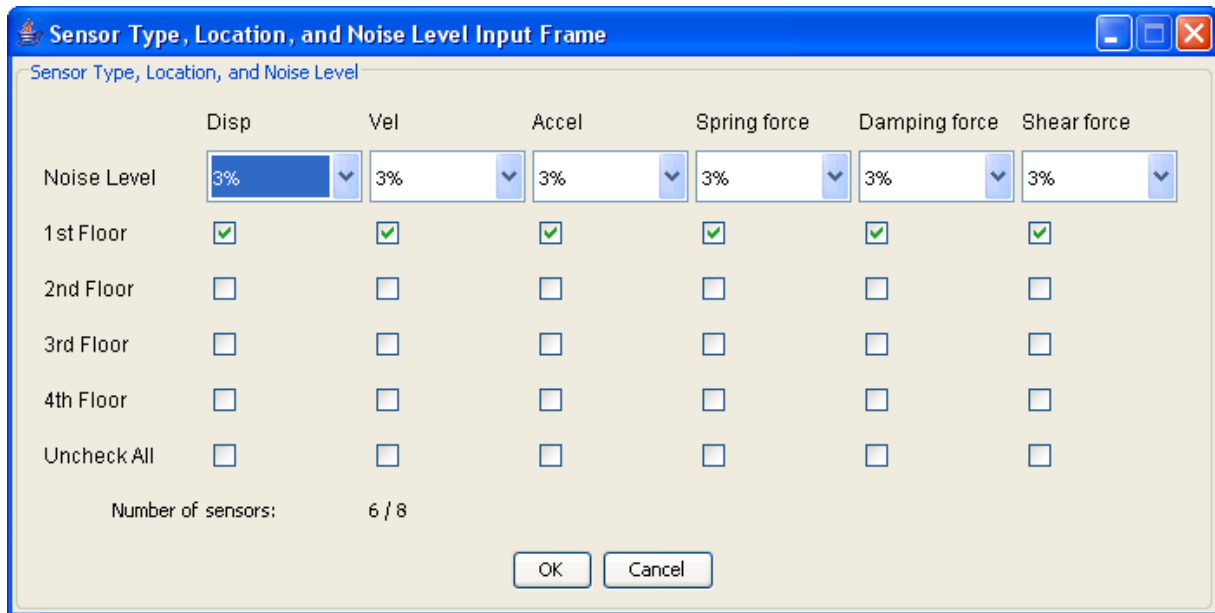


Fig. 4 Sensor dialog box.

The plot panels are used to show the measured responses and spectral function estimates. There are four plot panels, two of which are located on the left of the simulator and the other two are hidden under the animation panel. These two hidden panels and the animation panel are interchangeable by clicking the “Hide Virtual Building” or the “Show Virtual Building” button of the control panel. Users can choose the functions to be displayed by using the drop-down menu under each plot panel, which will open the “response selection window”. Provided functions on the menu are as follows:

- $y(t)$: Time history of the ground excitation and corresponding measured responses
- x - y : Response vs. response plot
- FFT: Fast Fourier transform of the ground excitation or the measured responses
- PSD: Power spectral density function of the ground excitation or the measured responses
- CSD: Cross spectral density function between the ground excitation and one measured response or between two measured responses
- Xfer: Transfer function between the ground excitation and one of the measured responses or between any two of the measured responses
- ACorr: Auto correlation function of the ground excitation or the measured responses
- Ccorr: Cross correlation function between the ground excitation and one measured response or between two measured responses
- Cohere: Coherence function between the ground excitation and the measured responses

- Impulse: Impulse response of the structure at sensor locations

In Fig. 2, the plot panel on the upper left shows the time history of the selected ground motion, which is El Centro earthquake record in this example. On the lower left, power spectral densities of the excitation and a few responses of the Bouc-Wen model are shown. Users can easily verify the peaks which represent the corresponding natural frequencies. Different responses for linear or nonlinear models can be displayed as shown in this PSD plot, or one response of different models also can be shown. (See Fig. 5)

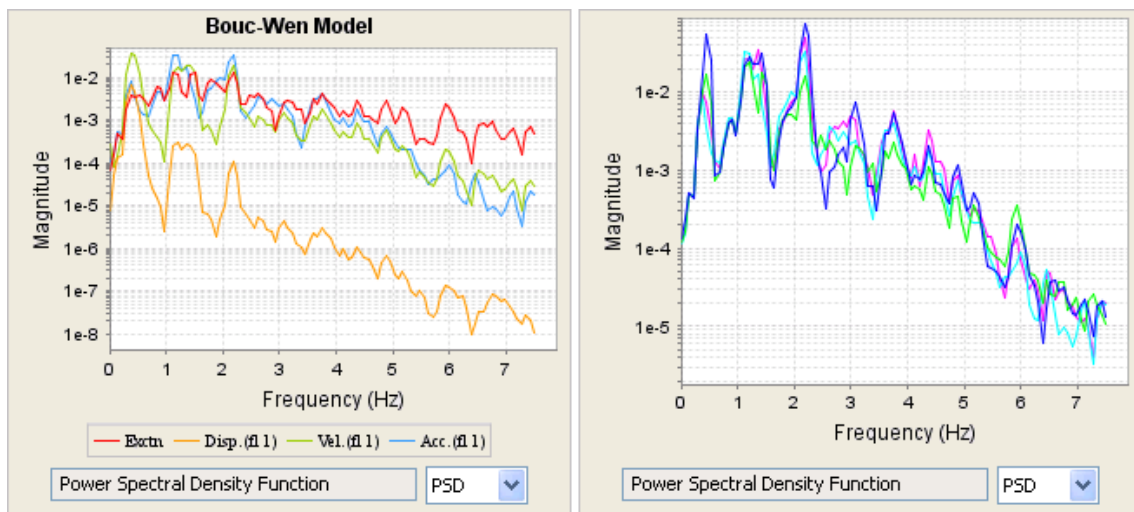


Fig. 5 Two kinds of plots

(Left: multiple responses of one model, Right: one response of multiple models)

4. Use of Virtual Laboratory

Two examples are provided in this paper to illustrate the unique features of the VL. More examples are available at the help page of this VL, which is accessed by clicking “Help” button or at <http://sstl.cce.uiuc.edu/java/esd/helppage/helppage.htm>.

4.1 Example 1

Consider a 4-story building model with a stiffness of 20,000 kN/m for the first and second floors and 15,000 kN/m for the third and fourth floors. Here, the VL's default mass and damping coefficients are used. A band-limited white noise excitation with a bandwidth of 15 Hz is employed, and the anti-aliasing filter is set at 5Hz. The task here is to compare the transfer functions of accelerations with the anti-aliasing filter on and off and verify the effect of the anti-aliasing filter. Discuss the transfer function without filtering considering the natural frequencies of the structure.

This simple example shows how important use of anti-aliasing filters is in an experiment. The natural frequencies of the structure are 2.66Hz, 7.24Hz, 11.18Hz, and 13.98Hz; however, because the cutoff frequency of the anti-aliasing filter is 5Hz, only the first mode is less than the Nyquist frequency. When the anti-aliasing filter is used, the transfer function has a clear peak and zero (see Fig. 8 left). Without proper use of the anti-aliasing filters, aliasing is introduced resulting in the noisy transfer function (see Fig. 8 right). Peaks around 1.6 Hz and 5.5 Hz which are not physically present (see Fig. 8 left) are the aliased third and second modes, respectively. In Fig. 8, two transfer functions have different frequency ranges. Because the gain of the filter decreases drastically in the frequency range beyond the cutoff frequency (i.e., the so called transition band), the transfer function from the filtered measurements in this range is not meaningful. Thus, the transfer function with the anti-aliasing filter is shown within the range from 0 to the cutoff frequency when the anti-aliasing filter is on (Fig. 8 left), while it is shown up to the Nyquist frequency if the anti-aliasing filter is turned off. Additionally, time histories of the measured ground excitation and acceleration at the first floor are shown in Fig. 6, and the typical force and response relationships for the linear and nonlinear models are shown in Fig. 7.

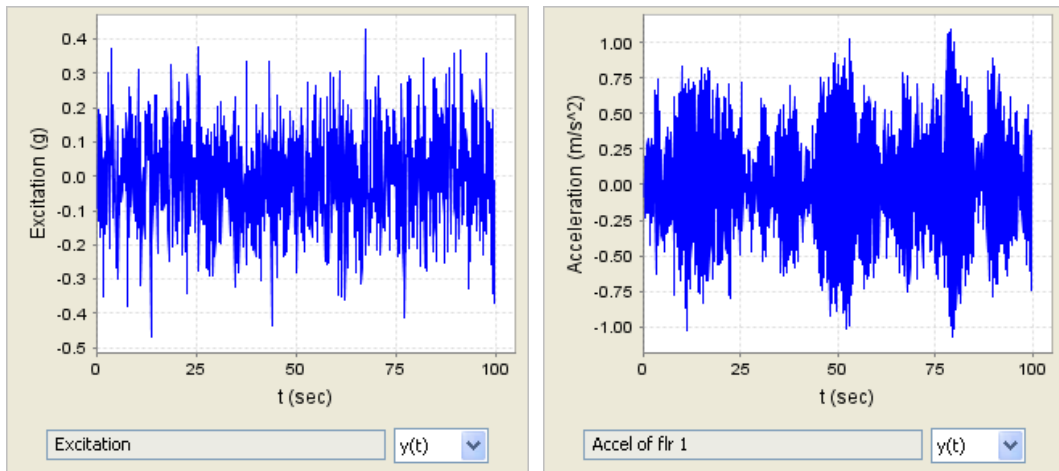


Fig. 6 Ground excitation and acceleration at the first floor for linear model

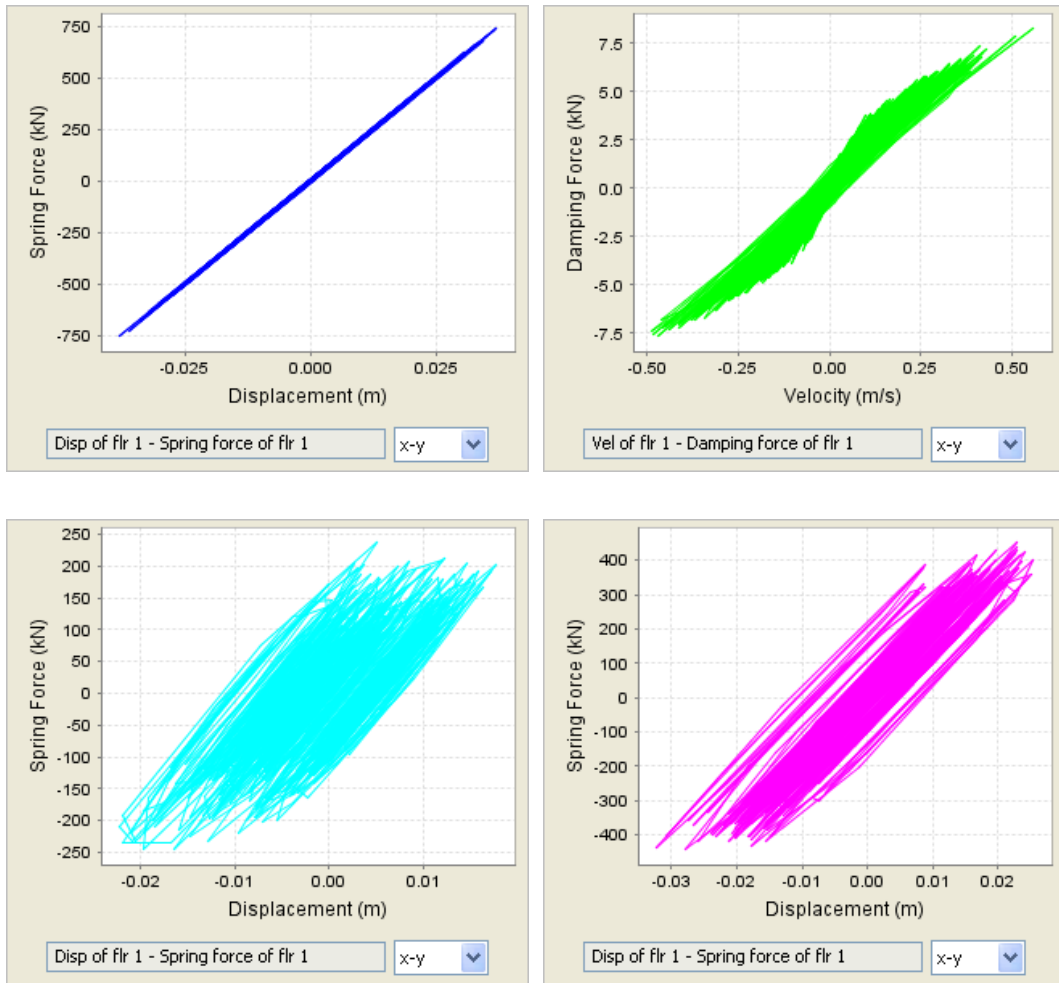
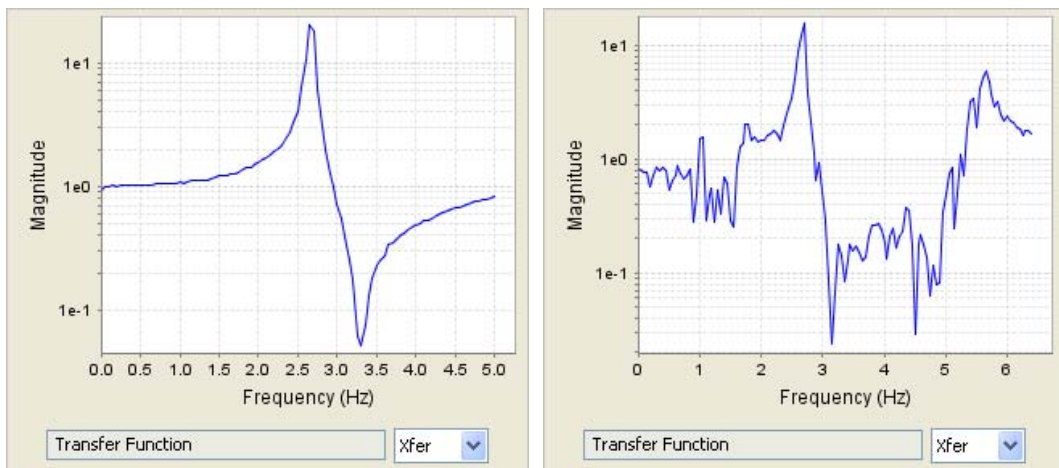


Fig. 7 Force and response relationship for different nonlinearities

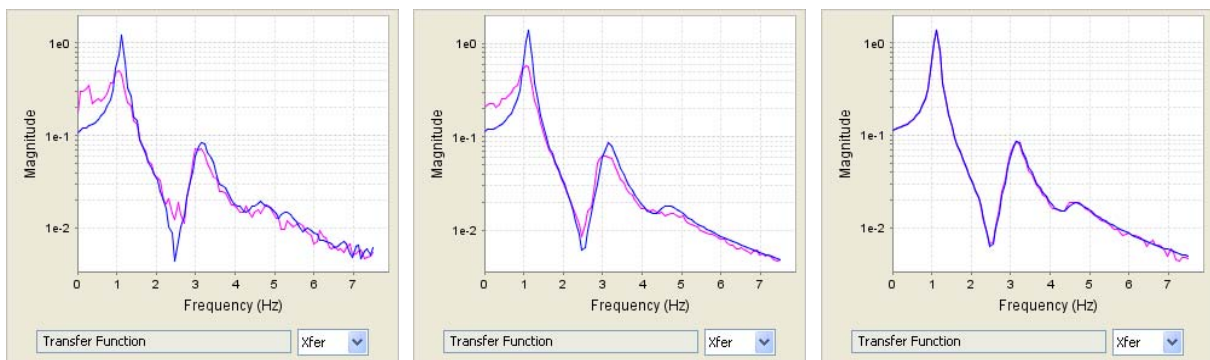


**Fig. 8 Transfer Functions of acceleration at the first floor
(Left: with AA filter, Right: without AA filter)**

4.2 Example 2

Assume the ground excitation of band-limited white noise is applied to 3-story building and use the default mass, damping, stiffness and amplitude of the random excitation. For the linear and bilinear models, plot and compare transfer functions from the input ground acceleration to the displacement of the 1st floor for $K_p = 500, 1000, 1800$ kN/m. Note that K_p is the post-yield stiffness for the hysteretic models.

In this example, the nonlinear effect on the dynamics of the structure is illustrated. Fig. 9 compares the transfer functions of the linear and bilinear models with the three different values of K_p . Because the stiffness before yield is 2000 kN/m, the smaller value of K_p means the higher nonlinearity in the system. When $K_p = 1800$ kN/m, the two transfer functions are very close to each other, implying response of this nonlinear model is almost linear. However, for smaller values of K_p , the locations of peaks are shifted to the left and the magnitudes are reduced because the nonlinearity introduces a lower stiffness and additional damping in the system.



**Fig. 9 Transfer functions of displacement of the first floor
($K_p = 500, 1000, \text{ and } 1800$ kN/m from left to right)**

5. Conclusion

The Experimental Structural Dynamics Virtual Laboratory (VL) has been developed to provide a unique opportunity to understand the conceptual and practical issues. Simulation of the essential aspects of dynamic testing such as data measurement and processing are implemented in the VL. By developing the VL using Java programming language, it can be accessed through the internet, allowing easy interaction for the users and providing a wide variety of the parameters for their virtual experiments. The participants who use the VL are expected to gain significant insight into experimental structural dynamics.

6. Acknowledgement

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7. References

- [1] Y. Gao, G. Yang, B. F. Spencer, Jr. and G. C. Lee, "Java-Powered Virtual Laboratories for Earthquake Engineering Education", *Computer Applications in Engineering Education*, Vol. 13, No. 3, 2005, pp. 200-212.
- [2] A. Newman, *Special Edition Using Java*, Que cooperation, Indianapolis, IN, 1996.
- [3] B. Eckel, *Thinking in Java*, Prentice Hall, 2003.
- [4] J. S. Bendat and A. G. Piersol, *Random Data*, John Wiley & Sons, 1991.
- [5] R. Sedgewick and K. Wayne, *FFT.java and Complex.java*
- [6] J. W. Tedesco, W. G. McDougal, and C. A. Ross, *Structural Dynamics: Theory and Application*, Addison-Wesley, 1998.
- [7] T. Belytschko and T. J. Hughes, *Computational Methods for Transient Analysis*, North-Holland, 1983.
- [8] G. V. Berg, *Elements of Structural Dynamics*, Prentice Hall, 1989.
- [9] W. H. Press, B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, *Numerical Recipes: The Art of Scientific Computing*, Cambridge University Press, 1987.