AC 2007-2657: ENHANCING THE LEARNING EXPERIENCE USING SIMULATION AND EXPERIMENTATION TO TEACH MECHANICAL VIBRATIONS

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Enhancing the Learning Experience Using Simulation and Experimentation to Teach Mechanical Vibrations

Abstract

Mechanical vibrations represent an important subject in mechanical engineering. This paper describes a simulation-based online laboratory that was developed to assist students in understanding the concepts of mechanical vibrations in the context of practical engineering applications. This system was designed with a flexible multi-layered graphical user interface, and it can be used to illustrate the physical phenomena of vibrations in a visual manner. It comprises interactive applications, virtual experiments, and auxiliary tools for instruction. Examples from real engineering systems provide the missing link between the theoretical concepts and the real engineering world, thus helping the students to capture the essential aspects of the problems in a mechanical model, making reasonable simplifying assumptions, and reducing this model into solvable problems such as single-degree-of-freedom free and forced vibrations. In addition, the remote control of real instruments through the Internet was integrated into the vibration laboratory experience.

Keywords: Virtual Learning Environment; Simulations; Web-based laboratory; Online Learning Environment

Introduction

Five categories of learning style models have been recommended in the educational literature[1,2,3]: sensing/intuitive, visual/verbal, inductive/deductive, active/reflective and sequential/global. Most textbooks and classroom teaching are intuitive, verbal, deductive, reflective and sequential, but this environment does not meet the needs of the second-tier students who are sensing, visual, inductive, active and global learners. Engineering educators have been reshaping the engineering curricula to respond and adapt to the ever changing nature of engineering practice where engineering is becoming more global, interdisciplinary and influenced by other disciplines such as computer science, information technology, nanotechnology, economics, etc. Some of the goals of these curriculum changes are to prepare students for a path of life-long learning and to get them involved in the communities where they live.

Self-learning environments are becoming increasingly important. They allow students to reach targeted levels of understanding and skill sets without incurring too great a demand for staff time. They include text documents containing theory and explanations, sometimes hyperlinked to interactive physical models, animations, video, diagrams and others. Computer programs that perform calculations can give the students insight into problems that are not discussed in class, except in very specialized courses. Linking complex theory and equations to numerical and animated graphical results increases understanding and information retention.[4] For instance, software packages such as LINCAGES[5] and SAM[6] are available for the analysis and synthesis of planar mechanisms. A PC-based vibration simulator for determining the first two natural frequencies and mode shapes of two stainless steel rulers was developed.[7] However, these and similar software packages could be characterized as providing advanced analytical functionalities that enable students to perform calculations. They were not intended for Web-based applications and are not suitable for use in a networked computing environment. The development of Web-based educational systems is very different from the developing process of traditional software in a variety of ways.

Today, the Internet provides a convenient and effective medium for facilitating a wide range of learning activities that allow for learning accomplishments beyond those achievable based on traditional learning materials. The recent explosion of the Web has provided a new system designed for distributing and sharing high-quality software. Such Web-based software applications have been demonstrated to be popular and intuitive to use. A Web-based interactive virtual laboratory system for a unit operations laboratory and a control experiment of separation processes such as distillation and drying in the chemical engineering education have recently been developed.[8] SoftIntegration Inc.[9] developed a Web-based interactive mechanism analysis and design system to provide the users with a convenient means to quickly obtain solutions to many mechanism design problems. The University of Illinois-Chicago[10] developed a website that contains analyses and animations of some simple vibration systems. The intent was to provide the student with a visual representation of the effects that various parameters have on the vibration of basic spring and mass systems.

Laboratory measurements can be accessed via remote laboratories, and web-based simulations and animations can also be adapted to fit the problem at hand. A student laboratory approach based on remotely accessible experimental setups was developed and piloted at Stevens Institute of Technology (SIT),[11,12,13] The various virtual and remote experiments that are currently available in this remote laboratory can be used through the corresponding Web page.[14] These Web-based tools include both remotely operated experiments based on actual experimental devices as well as virtual experiments representing software simulations. These tools facilitate the development of learning environments, which – possibly in conjunction with traditional hands-on experiments – allow the expansion of the scope of the students' laboratory experience well beyond the confines of what would be feasible in the context of traditional laboratories.

This paper describes a simulation-based learning environment to give the students a balanced combination of theoretical and practical skills. The theoretical part of this work is mainly concerned with the formulation of models and their numerical implementation, while the practical part deals with the computer implementation of the basic concepts of structural modeling, interpretations of the physical phenomena of vibrations and the application of these to engineering simulations. In addition, the Web-based vibration simulator described here incorporates experimental procedures and self-learning opportunities to reinforce the understanding of fundamental concepts of mechanical vibrations.

Interactive Learning Model

Vibrations are typically taught in undergraduate courses in a highly theoretical form since in-depth analyses of systems other than undamped, free vibrations quickly becomes mathematically intense. However, the students should ideally still have an understanding of the response of more complex and realistic vibration systems. Students often have difficulties visualizing some of the theoretical concepts presented. While typical homework problems in textbooks are certainly helpful, a student may have difficulty understanding what a mathematical solution to a problem means from a practical point of view. If students are provided with the means to perform experimentation and to apply the theory to real world situations, this can only be expected to lead to a better visualization and understanding of the theoretical concepts. The simulation system discussed here presents an attempt of integrating Web-based content and interactive multimedia techniques into the curriculum. The integrated platform provides an easy flow of data from theory to modeling and measurement, bridging the gap between theory and hands-on learning, as shown in Figure 1. It greatly enhances the students' understanding of vibration phenomena and assists them in grasping the concepts of mechanical vibrations in the context of practical engineering applications.

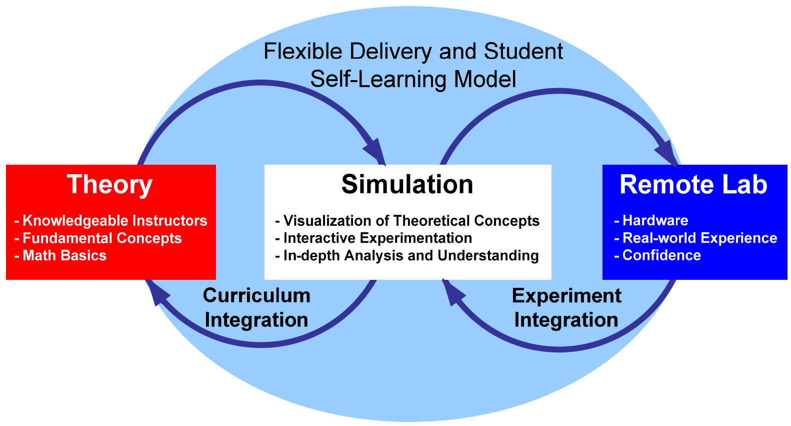


Figure 1: Interactive learning model

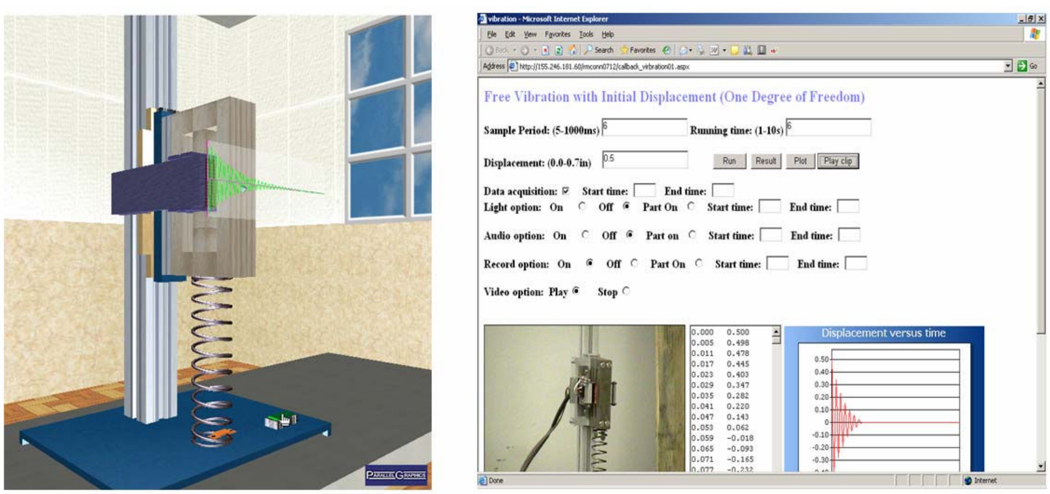
The developed system was designed with a flexible multi-layered Graphical User Interface (GUI), and it can be used to illustrate the physical phenomena of vibrations in a visual manner, as shown in Figure 2. It is to be run in any of the major Web browsers, and the programming solutions are using different languages and software development aids. The system integrates Java[15], Jython[16] and Virtual Reality Modeling Language (VRML)[17] to provide multiple users with virtual experiments over the Internet. Java applets provide platform independent support for the rapid development of GUIs and for processing user commands and communicating experimental results between the user and the application server. They also provide for the interactivity between the users and the VRML worlds and make the VRML fully functional and portable. Examples from real engineering systems (e.g. a water-tank system, a cam-follower system, a motorcycle, a car, etc.) provide a link between the theoretical concepts and the real engineering world, thus helping the students to capture the essential aspects of the problems in a model, making reasonable simplifying assumptions, and reducing these models into solvable problems such as free and forced vibrations.

Through instruments in the simulated environment, students gain a better understanding of the purpose of simulations and on how to use the simulation results when evaluating real vibration experiments. By clicking a RUN button, the experiments are animated, as shown at the left side of Figure 3. The students can navigate and examine the experimental setup, for example by rotating the view inside of the virtual environment using the standard VRML navigation features. This allows them to move around the experiment model and view it from any angle.

Furthermore, the students can zoom in at any positions in order to see the components of the experiment in detail.

Figure 2: Flexible multi-layered graphical user interface

In addition, the remote control of real instruments through the Internet was integrated into the vibration laboratory experience. This platform will allow the students quick and easy access to measurements, as shown at the right side of Figure 3. The online vibration experiment is a real-time exercise used to measure the natural frequencies and mode shapes of spring-mass-damper systems. A video streaming server and a LabVIEW server are connected to allow the students to see and hear the experiment while sending commands and receiving data through a LabVIEW script. The students can interactively control the experiments and obtain the corresponding outputs (including raw data, data plots, video/audio streams and recordings) in an integrated browser-based user interface.[18]



Virtual Experiment Model　　　Real-Time Vibration Experiment

Figure 3: Virtual and real-time remote vibration laboratories

Interactive Learning Modules

There is an increasing need to incorporate practical examples and industrially relevant case studies into engineering curricula in order to enable the students to better understand and visualize physical phenomena. The illustration of practical problems can provide a better learning experience and generate improved learning outcomes.[19] The purpose of the Web-integrated system presented here is to use interactivity for engaging the students in the learning process by presenting the material in a format that enhances the visualization of the mechanical vibration concepts through examples from real world products, such as for instance a cam-follower system, a water-tank system, a motorcycle and a car. The following sections briefly describe these interactive learning modules.

Module 1: Cam-Follower System

Typical industrial cam-follower systems are used in a wide variety of devices and machines to convert the rotary motion of a crankshaft into the oscillating or reciprocating motion of a valve. The most common application for cams is the valve actuation in internal combustion engines that have two or more cams per cylinder, as shown in Figure 4. They include a cam joint closed by a restoring force and a follower train containing both substantial mass and stiffness. Provided that the cam and follower remain in contact, this arrangement represents a single-degree-of-freedom (SDOF) system. This module serves to illustrate the free vibrations of an undamped spring-mass system. This type of exercise is beneficial because the students must first gain a complete understanding of the underlying theoretical principles involved and then apply them in creating a model of a physical situation which demonstrates these principles.

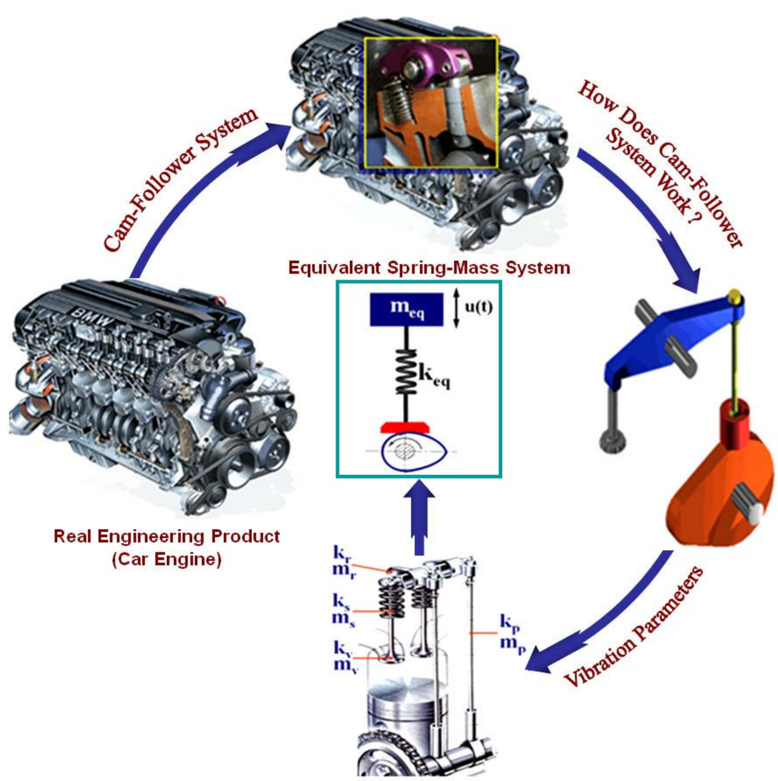


Figure 4: Cam-follower system and equivalent spring-mass model

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A sequence of pictures with animations, as shown in Figure 4, helps the students to develop a strong understanding of modal analysis of the real world system by investigating the vertical vibrations of the cam-follower system. As a study tool, the students can learn where to find cam-follower systems in real world products, better understand how cam-follower systems work, how to develop and simplify the system models and find the characteristic vibration parameters, how to apply the vibration theory learnt in class and build mathematical models for determining the natural frequency and mode shape of the system. The various masses in the system can be replaced by an equivalent mass, and while the elements of the follower system (pushrod, rocker arm, valve and valve spring) are all elastic bodies, here they are reduced to a single equivalent spring. Therefore, the cam-follower system can be idealized as a SDOF spring-mass system, whereby the students are able to vary the mass, spring constant, initial position and initial velocity of the mass.

Module 2: Water-Tank System

As another example, consider the swaying of a water tower under heavy winds or Earthquake conditions. The largest amplitude motion of a swaying water tower can be closely approximated as the motion of a second-order system. The effects of the wind can be modeled as a harmonic force acting on the center of the tank. Similarly to the previous example, the water tank can be considered as a cantilever beam that is fixed at the ground. For the study of transverse vibrations, the top mass can be considered as a point mass, and the supporting structure can be approximated as a spring in order to obtain a SDOF model, as shown in Figure 5.

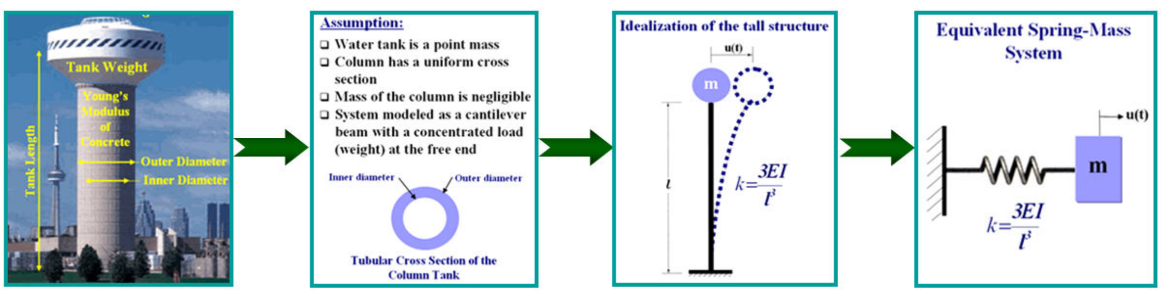

Figure 5: Finding the equivalent spring-mass system of a water tank

The students can easily review the graphical description of the simplified model, and thus they are enabled to learn at their own pace over the Internet. They can see and explore the effect of applying a harmonic force at the center of mass of the tank. They have also the option of choosing US Customary units or SI units for specifying the tank dimensions and other vibration parameters.

Module 3: Motorcycle-Suspension System

The front and rear suspensions of motorcycles work basically in the same way.[20] The most common kind of suspension systems on a motorcycle has a telescoping fork in the front and swing arms with shock absorbers in the rear. Using the system described here, the students can gradually develop a simple model with equivalent system values of the mass, stiffness and damping. A SDOF model of a motorcycle with a rider representing represents the simplest possible model, as shown in Figure 6. In this model, the equivalent stiffness includes the stiffnesses of the tires, the struts and the rider. The equivalent damping includes the damping of the struts and the rider. The equivalent mass includes the masses of the wheels, the motorcycle body and the rider. This model can still be further refined by representing the masses of the wheels, the elasticity of the tires as well as the elasticity and the damping of the struts separately with a two-degree-of-freedom vibration system.

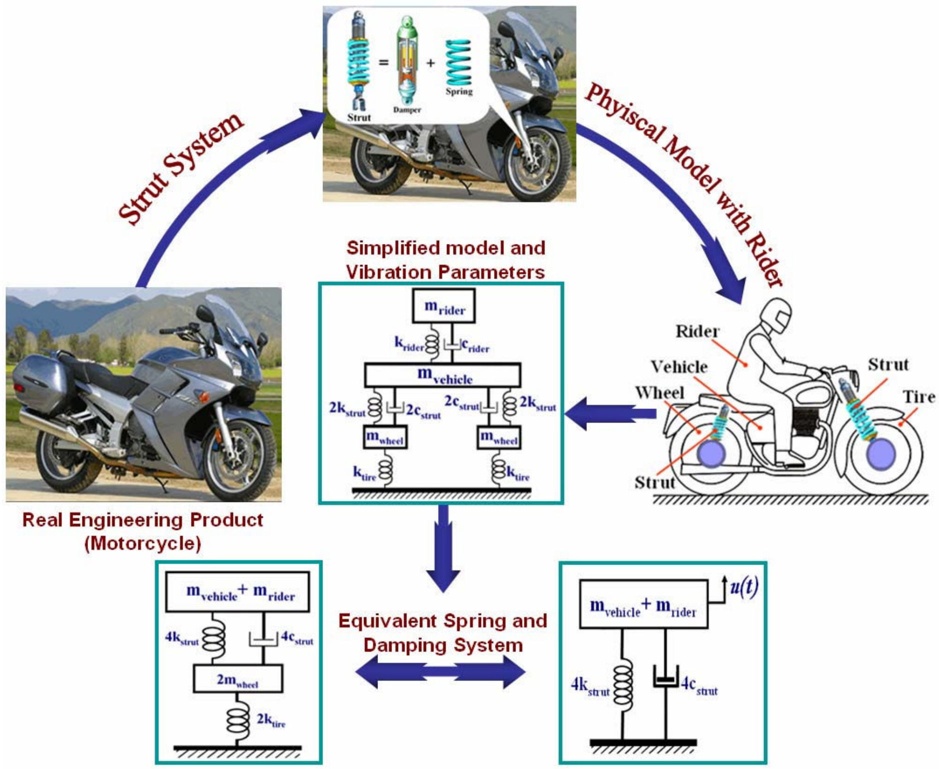

Figure 6: Modeling of the suspension system of a motorcycle

Module 4: Car-Suspension System

The suspension system of a car has two basic functions: 1) to keep the car's wheels in firm contact with the road in order to provide traction at all times and 2) to provide a comfortable ride for the passengers by isolating them from road noise, bumps and vibrations. While a car can also rock, tilt, sway, etc., one of the most important aspects of the ride quality (i.e. passenger comfort level) is the up-and-down motion of the car on its suspension springs. This motion can be described with a second order differential equation. A complete model of a car with passengers can be based on the front and rear suspension models, as shown in Figure 7. The schematic illustrates a step-by-step procedure that the student can follow in order to model the car suspension system, starting from finding where it is located inside the car, investigating the suspension system components including springs, shock absorbers and hydraulic actuators and animating the model in order to better understand how it works. The shock absorbers are modeled as linear viscous dampers and the tires are modeled as linear springs. The Web-based laboratory allows the students to vary the physical parameters in order to study the system response with different setups of the springs and dampers and under different loading conditions.

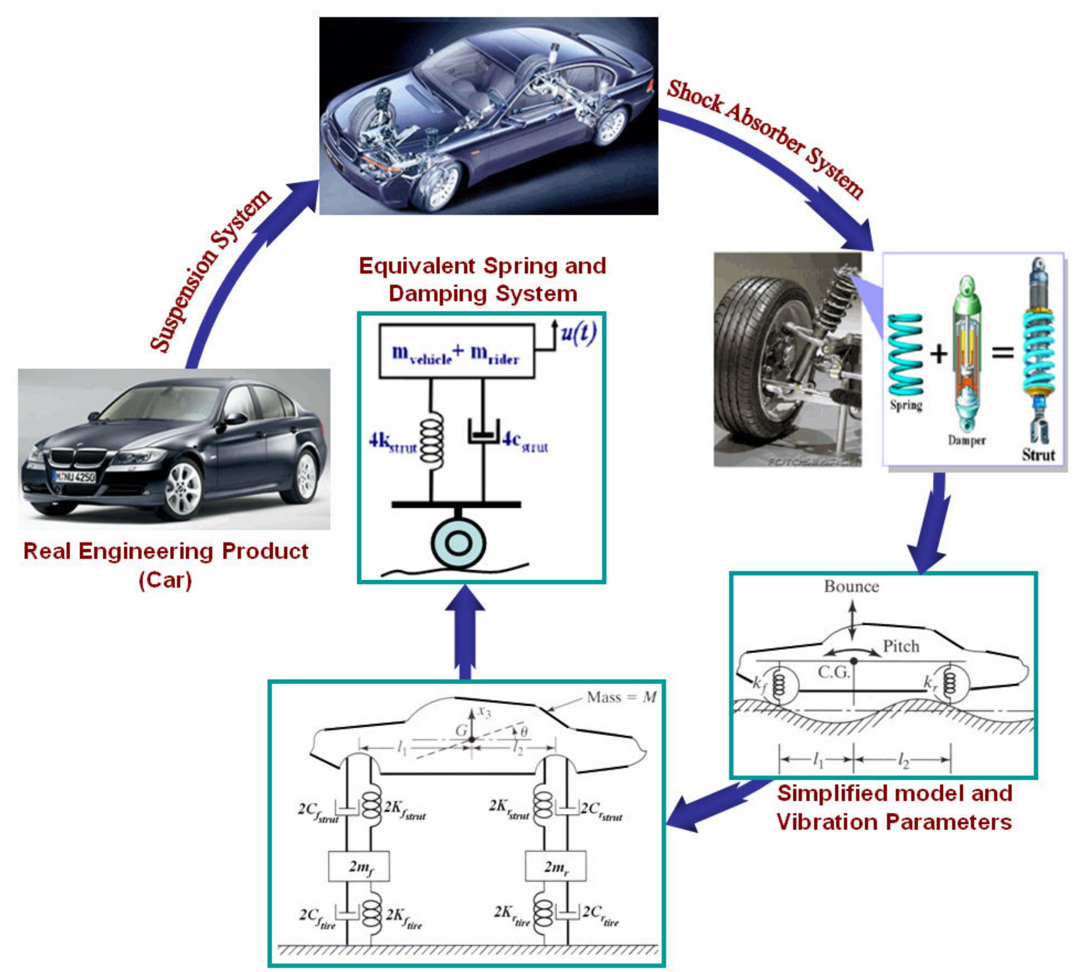

Figure 7: Modeling of the suspension system of a car

Module 5: Virtual Vibration-Experiment System

The graphical user interface also displays a 3-D representation of the vibration experiment using VRML. This helps the students to better understand the system response and allows them to select the various characteristic parameters of the experimental setup, as shown in Figure 8. In the free-vibration mode, the student can input appropriate values of the parameters such as to simulate underdamped, critically damped and overdamped vibrations. Using the damping ratios supplied by the students, the animation depicts the damped response of the vibration system, thus allowing the students to determine such things as the delay time, the rise time, the peak time, and the settling time. Under the forced-vibration tab of the GUI, the students can observe the system response to variations in the forcing frequency. Unlike a textbook problem, the animation brings the problem to life, thus allowing the students to gain a better physical understanding of the theory. An additional instructional benefit of this module results when the module is run at near resonance conditions.

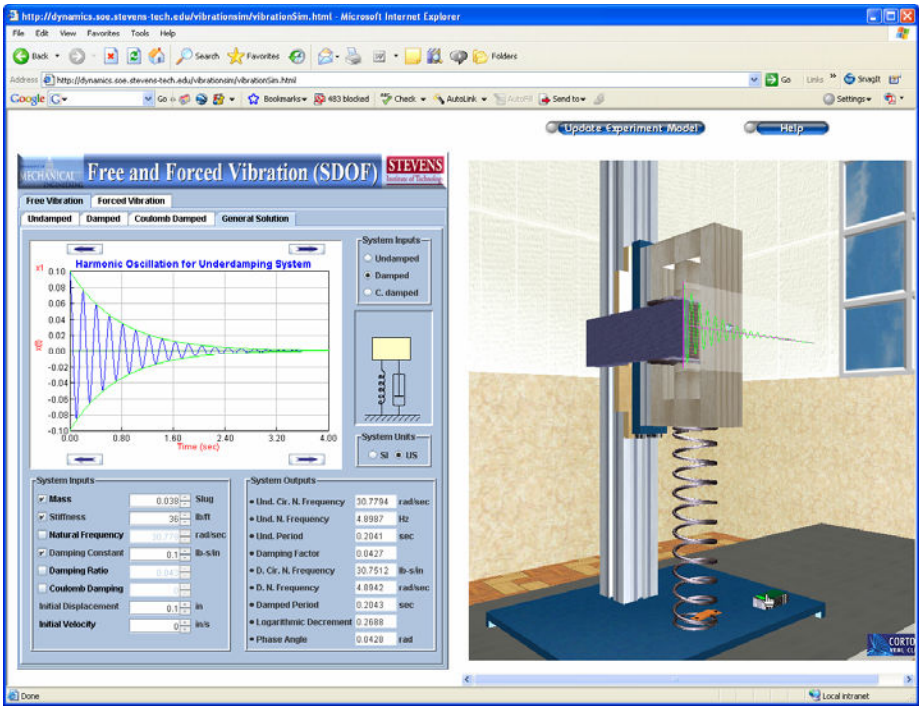

Figure 8: Components of multi-layered GUI at client site for vibration system

Assessment of pilot implementation

These Web-based animated teaching modules were successfully piloted in a junior-level mechanical-engineering course on mechanisms and machine dynamics in the Fall 2006 semester. To assess the students' reactions to these modules, they were asked to fill out a questionnaire at the conclusion of each of the four laboratory sessions using these modules. In these questionnaires, the students were asked to rate the modules with regards to five evaluation metrics on a five-point scale (1 - highly disagree, 2 - somewhat agree, 3 - neutral, 4 - somewhat agree and 5 - highly agree). The questionnaire is summarized in Table 1.

Table 1: Student questionnaire

Metric	1	2	3	4	5
M1: The material is very interesting and informative.					
M2: The outlined assignments enhanced my learning.					
M3: The directions given were clear, and good use of visual aids was made.					
M4: The laboratory is well integrated with the associated lecture course.					
M5: The laboratory manual is well written and organized.					

Table 2: Survey results

Metric	Average
M1	4.2
M2	4.1
M3	4.2
M4	4.2
M5	4.0

A total of 16 students were enrolled in the class, and 100% of the students participated in the survey. As summarized in Table 2, the survey results used to evaluate the Web-based animated teaching modules indicate the apparent level of success achieved in designing and implementing a comprehensive student laboratory experience as judge by the students. A more detailed assessment study of the learning effectiveness of the modules is planned for the Spring 2007 semester. If the planned more in-depth assessment generates similarly encouraging results, then further extensions of this environment to other courses of the mechanical engineering curriculum is planned in the future.

Conclusions

A simulation-based online laboratory that was developed to assist students in understanding the concepts of mechanical vibrations in the context of practical engineering applications is described. This system has a flexible multi-layered graphical user interface and can be used to visually illustrate vibration phenomena. It comprises Web-based interactive applications and virtual experiments. Furthermore, it is integrated with real instruments that are remotely controllable through the Internet. Various sample engineering systems provide a link between theoretical concepts and the real engineering world by capturing the essential aspects of the problems in a mechanical model, making reasonable simplifying assumptions, and reducing this model into solvable problems such as single-degree-of-freedom free and forced vibrations.

The main benefits of utilizing such a system are that the students get a better understanding of practical problems, that, instead of seeing problems statically in a textbook, they come to life with the animation and real-time experimentation system, and that the ease of use of the flexible multi-layered graphical user interface lets the students model complex practical problems without having to rely on heavy mathematics or tedious programming. Experimenting leads students to new avenues of exploration and to a better understanding of physics and engineering mechanics. Students learn mathematical modeling, and the modules give them an opportunity to test their models.

Acknowledgments

This work was supported by NSF Grant No. 0326309. This support is gratefully acknowledged.

References

[1] Felder, R. M. & Silverman, L. K., (1988), "How Students Learn: Adapting Teaching Styles to Learning Styles", Proceedings of the Frontiers in Education Conference, Santa Barbara, CA, USA, p. 489.

[2] Felder, R. M., (1993), "Reaching the Second-Tier Learning and Teaching Styles in College Science Education", Journal of College Science, Vol. 23, No. 5, pp. 286-290.

[3] Wang, S.-L., (1996), "Mechanism Simulation with Working Model", Proceedings of the Frontiers in Education Conference, Salt Lake City, Utah, USA.

[4] Slater, K. & Gramoll, K., (1995), "Vibration Visualization using Longitudinal Vibration Simulator (LVS)", Proceedings of the ASEE Annual Conference and Exposition, June 25-28, 1995, Anaheim, CA, USA.

[5] Erdman, A. G. & Riley, D. R., (1981), "Computer-Aided Linkage Design Using the LINCAGES Package", ASME Conference, No. 91, DET 121.

[6] SAM by ARTAS - Engineering Software at: http://www.artas.nl/

[7] Tan, A. A., Tang, T. & Paterson, G., (2005), "PC-Based Vibration Simulator for Assisting Learning of Mechanical Vibrations", International Conference for Engineering Education and Research (iCEER), Tainan, Taiwan.

[8] Shin, D., Yoon, E. S., Lee, K. Y. & Lee, E. S., (2002), "A Web-based, Interactive Virtual Laboratory System for Unit Operations and Process Systems Engineering Education: Issues, Design and Implementation", Computers and Chemical Engineering Journal, Vol. 26, pp. 319-330.

[9] Web-Based Mechanism Analysis and Design Toolkit by SoftIntegration at: http://www.softintegration.com/webservices/mechanism/

[10] Vibration simulations at: http://acoustics.me.uic.edu/Simulation/

[11] Esche, S. K., Chassapis, C., Nazalewicz, J. W. & Hromin, D. J. (2003), "An Architecture for Multi-user Remote Laboratories", World Transactions on Engineering and Technology Education, Vol. 2, No. 1, pp. 7-11.

[12] Aziz, E. S., Esche, S. K. & Chassapis, C. (2006), "On the Integration of Remote and Virtual Experimentations into a Comprehensive Student Laboratory Experience", Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Chicago, Illinois, USA.

[13] Aziz, E. S., Esche, S. K. & Chassapis, C., (2006), "An Architecture for Virtual Laboratory Experimentation", Proceedings of the ASEE Annual Conference and Exposition, Chicago, Illinois, USA.

[14] Remote laboratory homepage at Stevens Institute of Technology at: http://remlab.me.stevens-tech.edu/website/

[15] Java homepage at: http://java.sun.com/

[16] Jython homepage at: http://www.jython.org/

[17] Virtual Reality Modeling Language (VRML) at: http://www.w3.org/MarkUp/VRML/

[18] Li, Y., Esche, S. K. & Chassapis, C., (2007), "An Architecture for Real-time Remote Laboratories", Paper accepted for the 2007 ASEE Annual Conference and Exposition, Honolulu, Hawaii, USA.

[19] Tan, A. C. C., Paterson, G. D., Mathew, J. & Dunbabin, M., (2002)," Visualization of Vibration Mode Shapes to Assist Students in the Learning of Mechanical Vibrations", World Transactions on Engineering and Technology Education, Vol. 1, No. 1.

[20] Rao, S. S. (2004), "Mechanical Vibrations", 4th Edition, Pearson Prentice Hall, Upper Saddle River, NJ, 07458.