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Virtual Labs in the Engineering Curriculum

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Abstract
Computer simulations have been developed for use as student exercises to illustrate concepts required for various engineering courses. These simulations or Virtual Labs are highly graphical and interactive to help undergraduate students understand basic concepts by graphically solving problems and by visualization of real-time parametric changes. These Virtual Labs (or VL's) can be used productively in conjunction with existing laboratory experiments as pre-lab exercises, but the more important benefit is realized in cases of concepts that have no experimental support and in courses that traditionally do not have an associated laboratory course. These VL's are generated in the software package LabVIEW, which offers graphical interfaces for the student and can be formatted as standalone files, which the students can download and access at their convenience, without the need for LabVIEW software. Currently five VL's have been generated and several have been evaluated by students in appropriate classes.

Introduction
Computer-based virtual instrument software is used extensively in upper-level mechanical engineering labs at Rice University. The students interface with the experiment through virtual instruments on a computer screen. LabVIEW software running on the computer performs data acquisition, data storage, graphic presentation, and in some cases controls system parameters[1]. Additionally, analysis virtual instruments were developed using LabVIEW software to facilitate data analysis in certain experiments that required extensive data reduction for the desired final results[2]. In certain experiments, the students had difficulty in understanding the experimental results and virtual labs were developed to be used as pre-labs for greater understanding in the actual experiment. These virtual labs showed promise in helping student understanding of the actual labs and so a proposal was initiated to develop multiple virtual labs that would enhance student learning not only in the lab setting, but also, in non lab environments: as homework/class assignments in lecture courses as well. This proposal was accepted and the development of these virtual labs is being conducted under a grant from Rice University's Brown School of Engineering Teaching Grants Program.

Need - Visual Learners
The value of demonstration and laboratory experience has long been recognized in education. The engineering curriculum relies heavily on laboratory programs to provide the student with a real life experience to augment lectures. These classes provide a necessary "hands on" experience

for the student to reinforce the theory learned in classroom lecture. The virtual labs proposed in this paper are not intended to replace the existing "wet" labs, but are intended to augment existing laboratory experiments as pre-labs and to provide a visual learning experience for concepts presented in courses, which do not have associated lab courses.

The research area relating to the theories of learning is a very active field, but the need for visual learning is present in most theories[3,4]. Many students are visual learners and these VL's address their need for highly graphical presentation of concepts presented in lecture format.

LabVIEW Software

LabVIEW software provides a very graphical interface for the user. Many papers address the usefulness of LabVIEW in education[1,5,6]. LabVIEW has a front panel for presentation of data and status, and a graphical programming approach that allows easy use of a library of functions or subroutines. A typical control panel is shown in Figure 1. These control panels have been used very successfully for presentation of data acquisition in laboratory experiments. This usefulness carries over to the VL's as well for presentation of computer-generated information.

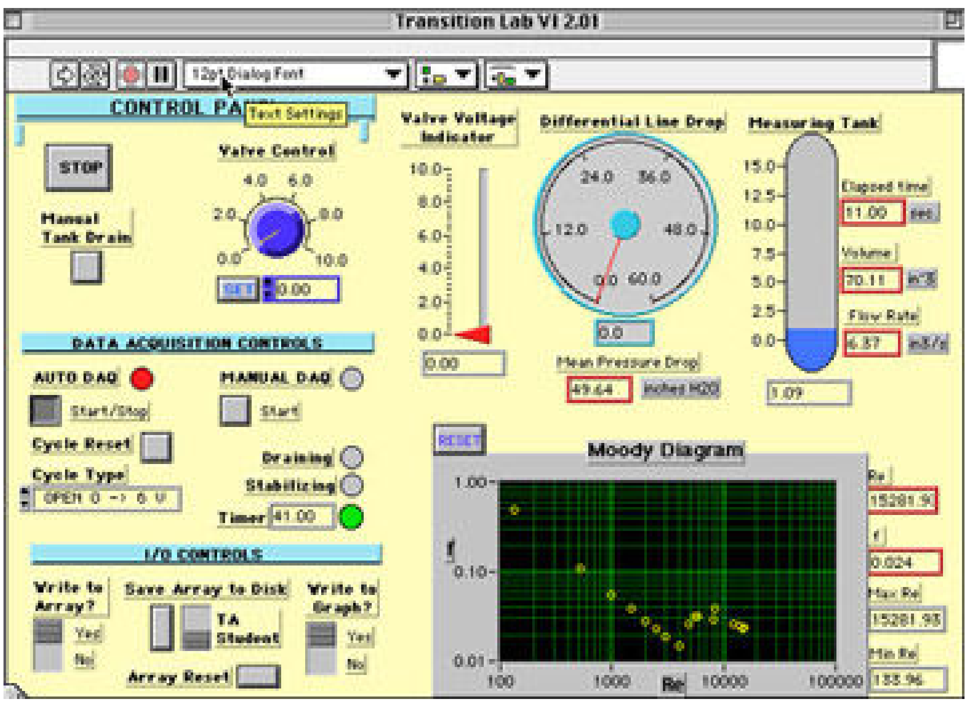

Figure 1: Typical Control Panel for Data Acquisition in an Experimental Lab

LabVIEW is the accepted standard in visual programming environments[7] and is used extensively in undergraduate engineering education[5, 6, 8, 9]. In fact, Dr. Kauler states, "Engineers are primarily goal-oriented, and a language is a tool to achieve the goal. The tool should do so as easily and quickly as possible. A project should not become bogged down in the distractions of a language's intricacies, yet this is often what happens. The learning curve for a language is an important factor as is the poor retention of learning due to infrequency use of a language. The latter phenomenon is a common problem for engineers, who tend not to spend all of their time

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using a language."[8] Similarly, King *et al.* state, "The language is a means to an end. That end is to do a given project, but in the process students can also learn the high level concept of the design of the program, freed from most of the minutia of low level, text-based development systems."[9]

This V L concept is not limited to using LabVIEW software, and other programs are being considered for better simulation of certain dynamics conditions requiring videos, etc.

Virtual Lab Development

The spirit of the VL concept is that the student is required to solve a problem in a graphical manner by adjusting parameters that vary the agreement of theory with the computer-generated or otherwise provided data. This interaction provides visualization of the effect of the various parameters in real time and reinforces the student's understanding of the basic concepts. The benefit of interaction for solving problems that exhibit dependence on multiple parameters brings up an interesting challenge. In order for the student to realize the full potential of the Virtual Lab, the author must carefully design the exercise to utilize the interactive features. For example, in one virtual lab (described in the next section), students are provided with two panels for column buckling analysis and design. In the first panel, students enter given data (column geometry, material properties, and desired safety factors), and the virtual lab generates the critical load that the column can withstand for these given parameters. However, this is not necessarily an interactive problem, because the solution is sequential. In other words, given a set of known parameters, solve for the critical load on the column. In the second panel, the students are presented with a virtual lab for design of columns. In this exercise, students enter known parameters (desired safety factor and the load to be carried), and then the students can make a variety of choices in order to meet these criteria. Framed as a design problem, the student can change material properties, cross-sectional geometry, column height, and end conditions to see the effects on the final column design. As demonstrated by this example, the virtual lab truly shines when there is not a single answer to a given problem.

One significant advantage of using LabVIEW software for this purpose is that once the virtual lab is developed, it can be converted into a "stand alone" format that can be put on a course web page. The student can download the set of files and run the VL at his/her convenience on a computer that does <u>not</u> have LabVIEW software. This allows the student to run the VL on a personal computer in the dormitory, the library, or any other location, rather than on only a limited number of designated computers on campus. Clearly this aspect provides a tremendous amount of flexibility for use by the students with either lecture or lab courses. It should be noted, though, that Rice University has a site license for LabVIEW, allowing broad distribution of the software across campus computers, if necessary.

Virtual Labs Developed

1. **Pre-Lab for Wave Tank II Experiment**
   The VL for this experiment is a simulation of a boat's motion with incident beam waves. A second order differential equation of a system with a forcing function is used in the experimental analysis and the VL simulation to model the boat's response to the generated waves. The student solves several cases that reflect different values of natural

frequency and/or damping ratio. Once a case is chosen the computer generates a set of "data points". The student is required to solve for damping ratio and natural frequency for a chosen case using graphical techniques. (More detail of this simulation is discussed in Appendix A.)

2. **X-Y Plotter Analysis**
   This experiment gives students a chance to observe the frequency response of an electromechanical system (an x-y plotter) and to manipulate the experimental data in ways that reinforce several basic concepts presented in a system dynamics course. The student is provided with amplitude versus frequency data for the x-y plotter, and then performs a brute-force optimization using dials on the LabVIEW front panel to make a theoretical transfer function fit the experimental data. Two transfer function models are used in the experiment to give students an understanding of the effects of poles, zeros, break frequency, natural frequency, and damping ration on the frequency response. (More detail of this simulation is discussed in Appendix B.)

3. **2nd Order Differential Equation System**
   This virtual lab is meant to give students a thorough understanding of second-order system behavior. The standard form of the second-order differential equation is presented [$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = f(t)$], along with the corresponding parameter values for systems in three domains: mechanical, electrical, and fluid. Unforced and forced time responses are displayed. Students can vary the basic system parameters (ζ and ω_n) or they can vary the domain-specific parameters (mass, spring stiffness and damping for mechanical; resistance, inductance, and capacitance for electrical; fluid resistance, fluid capacitance, fluid inertia for fluid systems).

4. **Converging Nozzle**
   This virtual lab gives a visual presentation of nozzle geometry, pressure distribution, temperature distribution, and mass flow for a conical converging nozzle with isentropic flow. The inputs are upstream pressure, downstream pressure, gas molecular weight, and nozzle geometry. It is particularly useful to graphically show that the flow transition into "choked" flow as the nozzle back pressure is reduced. This VL is not designed for a specific experimental lab and is anticipated to be used for class or homework exercises.

5. **Column Buckling**
   This virtual lab gives students in machine design courses two tools. First, they can interactively change end conditions, geometry, and material properties for a column and find the resulting critical load for failure. Second, they can iteratively design columns for given loading conditions and safety factors. In the second case, appropriate equations (Euler, Johnson) are used by the VL depending on the column geometry.

Virtual Lab Distribution

VL's are accessed by downloading a zip file containing all the necessary files for installation and execution of the VL on a non-LabVIEW computer. This method was employed for the X-Y Plotter VL, and it proved feasible and successful, as all students were able to access the software. The LabVIEW Application Builder is an add-on package for creating the stand-alone applications. When used with the Application Builder, a LabVIEW system can create programs that operate as stand-alone applications. The end user can run the executable, but cannot edit it. The result of the Application Builder is a folder containing all the necessary files to run the VL. These files are zipped and posted to the course web site.

Virtual Lab Assessment

Two VL's were used in different classes in the fall semester of 2003. One class contained 30 students and the other 25. Both VL's were used in conjunction with existing laboratory exercises to get valid comparisons and to help the student in formulating the evaluations. These VL's were being judged as to their enhancement to the actual experimental lab. The X-Y plotter analysis VL was converted to a stand-alone and was put on the course web page. Students downloaded the VL and carried out the exercise at their convenience (in a computer lab or on their personal computer). The students answered questions and gave evaluation of the VL.

After completing the X-Y Plotter VL, students were asked to include a typed 100-200 word conclusion of how the LabVIEW analysis helped (or impeded) their understanding of frequency analysis and the effects of system parameters on system behavior. In addition, they were to include comments on the utility of LabVIEW versus Excel for the experiment.
Responses can be summarized as follows:

Excel is better for comprehension	**V L is better for comprehension**	**Both have advantages (besides comprehension)**	**Disliked V L**
0	25	15	0

For the case of the pre-lab for the Wave Tank II Experiment, the VL was on several computers in a lab room and the students did the exercise during a special lab period. Due to time constraints, this VL was not made into a stand-alone for this evaluation. After completing the Wave Tank II VL the students answered questions and gave their evaluation of the virtual lab. In this case, thirty students were asked questions to evaluate the usefulness of the VL. A summary of the responses is shown below. Overall the responses were extremely positive. Virtually all students felt the VL helped their understanding of the concepts.

Concept	Boat Roll and Boat Acceleration Relationship	Damping Ratio Affects	Phase Angle and Natural Frequency Relationship
No Help	2	1	2
Some Help	2	6	2
Very Helpful	26	23	26

Table 2:Wave Tank II Summary of Understanding Concept Responses by Students

Both VL's were very favorably received by the students (typical student comments are in Appendix C).

Conclusions

The virtual labs described in this paper were found to help students visualize the results of two specific laboratory assignments. These findings show these V L's can give strong support to the student that is a visual learner. A significant advantage of the virtual labs is that many cases can be evaluated quickly. From the work so far:

- Virtual Labs can be generated in LabVIEW software and distributed to students as "stand alones" via the course web pages
- VL's can provide a significant learning enhancement tool for all students
- VL 's can be used productively as pre-labs for traditional "wet" labs.

Future Plans

Based on the initial successes of the Wave Tank II Virtual Lab and the XY Plotter Virtual Lab, the authors are planning further development, such as:

- Both of the VL's tested were very specific and related to a given experiment. The VL's being developed now are not addressing a specific experiment and are more general in scope *e.g.* a second order differential equation for a mass-spring system with damping. Five more VL's are to be completed to finish the Brown Grant project. This effort is expected to be completed by the end of the summer. This will allow student evaluation in the fall semester of this year.

- Using statistical functions, a controlled amount of error can be included in the computer generated "data". This will give the student a feel for the effect of variations in the standard deviation and other statistical measures on the resulting data set.

APPENDIX A
Wave Tank II Virtual Lab

Wave Tank II Background – This experiment is a study of the steady state boat roll under the influence of beam waves. A simple spring-mass-dash pot system is used to model the boat's motion, and a forcing function is included in the second order differential equation describing this motion. A mechanical wave generator is driven by a frequency generator to produce wave trains of different frequencies in a wave tank. A model boat is located in the wave tank and is equipped with a masthead accelerometer. Also the wave tank is equipped with a water level sensor to provide data on the wave heights produced by the wave generator. Multiple runs are made at different frequencies and the resulting wave height and masthead acceleration are recorded. A LabVIEW vi is used to acquire data and store the data to a file that can be down loaded to a floppy disk. This data can be analyzed by an analysis vi to evaluate the natural frequency and damping coefficient of the model boat.

The V L for this experiment is a simulation of the second order differential equation of a spring-mass-dashpot system with a forcing function. The student does several cases that reflect different values of natural frequency and/or damping ratio. Once a case is chosen the computer generates a set of "data points". The student can see plots of the masthead acceleration and wave height at any chosen forcing function frequency. The computer generated data points are presented on a magnification factor plot as magnification ratio vs. frequency ratio. The student adjusts the damping ratio to get a curve fit to the data points. Additionally a phase angle vs. frequency ratio is displayed with the data points and theory curve. Adjusting the damping ratio gives the curve fit for this plot also. The student now is prompted to note that when the frequency ratio is one, the phase angle is always 90 degrees between the boat roll and wave height no matter what value of damping ratio is specified. This screen is shown in figure 2. The student then goes to a graph on another portion of the control panel where six seconds of boat roll, wave height, and masthead acceleration data are displayed. The phase angle between boat roll and wave height is also displayed on this graph for the current input frequency. The student adjusts the input frequency until the boat roll and wave height are 90 degrees out of phase, and this input frequency is the natural frequency (the frequency ratio is 1). The student records the natural frequency and damping ratio for that case. Another case is chosen, and this process is repeated for six cases. The student turns in a hard copy set of answers.

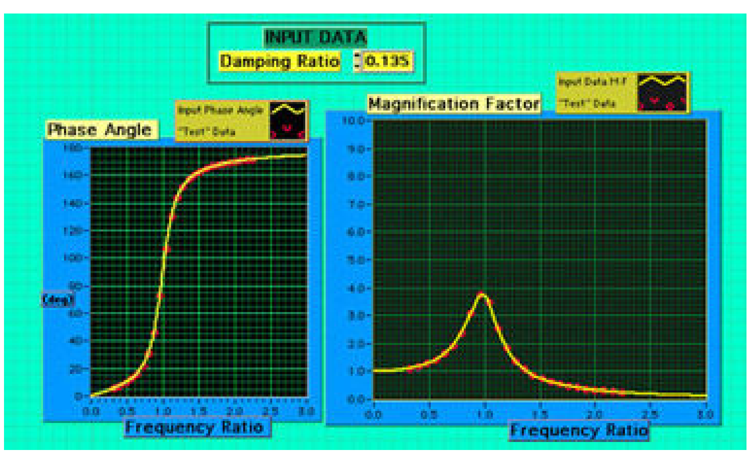

Figure 2: Magnification Factor and Phase Angle vs. Frequency Ratio

APPENDIX B
X-Y Plotter Analysis

This experiment is an exercise in creating a black-box model of an X-Y recorder and generally follows the iterative procedure of data acquisition, model representation, identification, simulation, and validation. To reinforce important concepts of the course, a transfer function is the selected model type, frequency response (amplitude only) is the identification method, and a simple optimization method is used to compare real and simulated output.

This experiment gives students a chance to observe the frequency response of an electromechanical system and to manipulate the experimental data in ways that reinforce several basic concepts presented in the course. Students performing the data reduction for this experiment are familiar with transfer functions, have practiced manually sketching straight-line, asymptotic frequency-response plots, can obtain and use the analytical expression for the magnitude of a transfer function, and have been introduced to the terminology of poles and zeros.

A copy of the graph paper from the plotter, with annotations, is provided to the student. Each vertical line is the peak-to-peak pen-trace at the input frequency indicated. The students complete a detailed optimization procedure using Microsoft Excel in order to determine system parameters for two transfer function models, including break frequency, natural frequency, and damping ratio for the second order system. The laboratory exercise to this point is identical to that described in [10], and all materials were provided to the authors by Dr. R. A. Layton.

Upon completion of the Excel analysis, the students repeat the optimization using brute force via the LabVIEW V L developed by the authors rather than using the optimization toolbox in Excel. With the V L, they can see in real-time the effects of each unknown parameter on the frequency response plot, thus providing additional insight into the relationships between these parameters and the behavior of the electromechanical system. This feature was notably absent during the Microsoft Excel portion of the exercise.

V L Procedure:

1) Complete the laboratory exercise using Microsoft Excel, as detailed in [10].
2) Download and install the x-y plotter virtual instrument from the web site. (See Figure 3)
3) Enter the frequencies and amplitudes from the chart of the experimental data.
4) Verify the calculated data in the columns with your Excel file
5) Adjust the break frequency and static gain knobs to fit a line to the data points.
6) Adjust the natural frequency and damping ratio bars in the first model so that the theoretical curve fits the experimental data.
7) Starting with the values from the first model, adjust the values in the second model to get an even better fit using the same methods used in step 4.

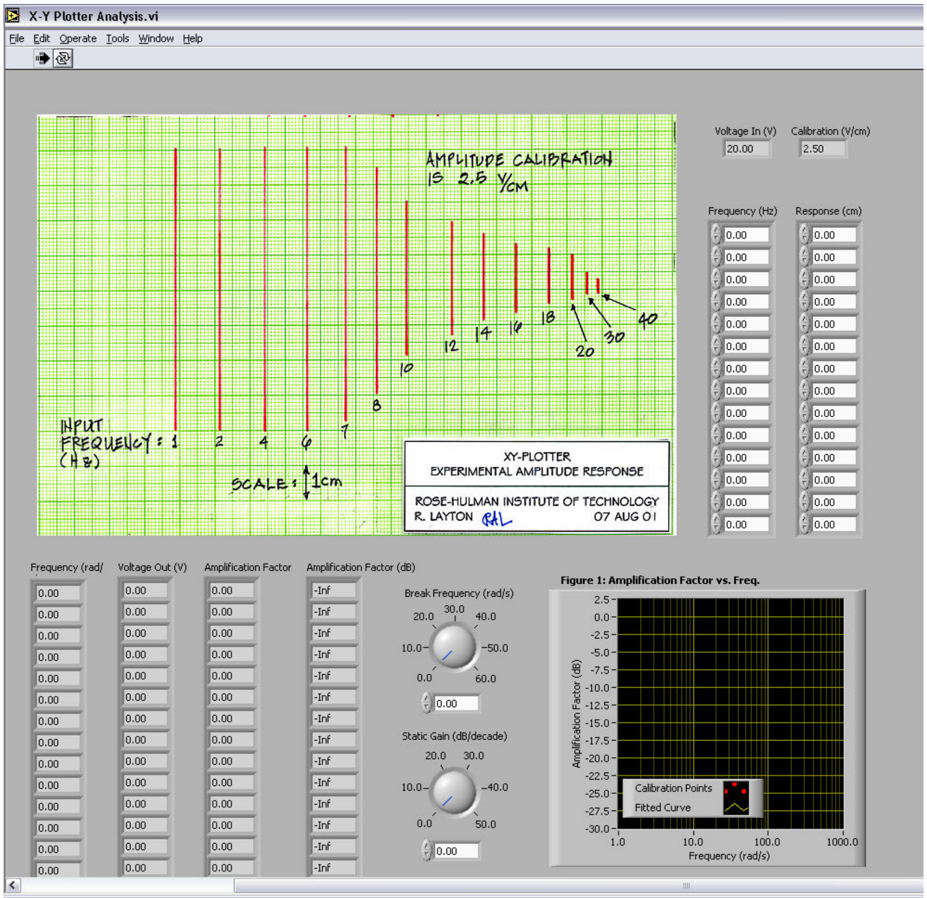

Figure 3. LabVIEW Front panel for X-Y Plotter virtual lab

APPENDIX C
V L Evaluations

For each of the VL's used in the fall semester, the students were required to evaluate VL with respect to the existing lab. The results of these evaluations are shown below.

I. Wave Tank II

Virtually all students felt the VL helped their understanding of the concepts. Although only typical comments are shown, they were all positive with some constructive input for improvement.

1.) Comments on the virtual lab:

Clears up loose ends…
A very useful program that makes previously difficult concepts simple.
Better than the real thing!
It was easier to recognize trends with this software.
I got a lot more out of the virtual lab, but I still think that the hands-on lab is still needed to actually see what is happening.
It was very informative. The relationships between different variables at (of) the experiment were made easier to pick up.

2.) Suggestions for improving the virtual lab presentation:

None. The virtual was very well done.
Change the program to allow smaller increments for damping ratio.
To have the virtual lab first; then have the regular lab.
Larger variation of damping ratios …would be more instructional.
There are a couple of kinks, but overall the lab does a good job of demonstrating the concepts.
It's perfect!

II. X-Y Plotter Analysis

None of the students felt that Excel was a better tool than the VL for understanding the effects of varying system parameters on frequency response. Many of the students (15) felt that the lab emphasized the advantages of both software tools. One student said it well:

"LabVIEW added a great deal to my understanding of this problem. The ability to adjust the values of the natural frequency, break frequency, and damping ration and see those changes immediately on the magnitude plot gave a very clear cut understanding of how the parameters affect the theoretical and actual system…I feel that the LabVIEW part of the lab really solidified my understanding of what was happening. On the other hand I do not think that I would have gained the understanding from just the LabVIEW portion. Mainly, I believe that the two portions acted together quite well. The first lab gave a more grunt approach of solving the problem and gave a good understanding of the error associated with the curve fit. In addition for those students who do not know how to use Excel, a good tool, it gave them some practical experience. On the other hand LabVIEW allowed for a more general understanding of how the different variables interact with each other."

Other comments included:

"Offered a nice interactive environment which was very helpful in understanding how different parameters affect the outcome of the Bode plots"
"LabVIEW XY Plotter helped enormously in the comprehension of this lab"
"The LabVIEW analysis was superior to the Excel analysis in every way"
"LabVIEW is undeniably better for promoting understanding of systems. Excel was a better tool for finding the minimum error in the fit."
"Great additional tool for increasing the understanding of frequency analysis"
"It was much easier to vary the parameters, so more experimentation was done by the student, increasing their understanding of the behavior of systems."
"The two portions acted together quite well."

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Biographical Information

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