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VIRTUAL LAB FOR SYSTEM IDENTIFICATION OF AN ELECTROMECHANICAL SYSTEM

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ABSTRACT

A stand-alone virtual instrument (vi) has been developed to augment an experimental system identification laboratory exercise in a required mechanical engineering course on system dynamics. The Virtual Lab (VL) was used productively as a post-lab exercise in conjunction with an existing laboratory experiment for system identification. The VL can be formatted as a standalone file, which the students can download and access at their convenience, without the need for LabVIEW software. The virtual lab presented in this paper used the experimental identification of a transfer function for an xy recorder developed at Rose-Hulman Institute of Technology. In the original Rose-Hulman experiment, students view a video of the acquisition of frequency response data for an X-Y recorder. Then, students complete a detailed optimization procedure using Microsoft Excel in order to determine system parameters for two transfer function models. This paper describes using the Virtual Lab to extend the original lab exercise into an interactive mode. The students complete the Microsoft Excel part of the exercise, but then repeat the optimization using brute force via the LabVIEW based VL developed by the authors, rather than using the optimization toolbox in Excel. With the VL, students 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 is notably absent in the Microsoft Excel portion of the exercise. Although this exercise uses simple dynamic models, the combination of Excel and LabVIEW approaches provide an insightful introduction to experimental system identification. In this paper, details of the VL are presented, including the functionality of the VL and methodologies for disseminating the VL as a stand-alone piece of software. Finally, some assessment results for the original (Excel version) and VL methods of presenting the laboratory exercise are discussed.

INTRODUCTION

A typical system dynamics course covers basic concepts in modeling of mechanical, electrical, fluid, and thermal systems based on constitutive laws, and the analysis of system response in both time and frequency domains. Several system dynamics textbooks include frequency domain topics as a critical component of the introductory course material [1-3], and as such, laboratory experiments that improve dynamic visualization and provide insight into the significance of mathematical expressions are often used to supplement such material [4]. As stated in [5-7], demonstrations that target visual learners and hands-on experiences that target sensor learners are important. Therefore, the virtual lab described in this paper was developed to improve the pedagogical effectiveness of a system identification experiment such that the interactions of the system parameters and mathematical expressions which govern the parameter behavior in frequency domain are clearly conveyed to the student.

Course Description

Students pursuing bachelor's degrees in mechanical engineering at Rice University are required to take the course MECH 343 *Modeling Dynamic Systems*, typically in the junior year. The four-credit-hour course consists of three lecture hours per week, plus five laboratory experiments spread over the semester. Typically about thirty students are enrolled in the course each year. The experiment described in this paper is the final laboratory experiment of the semester, since it coincides with the more advanced frequency domain topics in the course.

LabVIEW for Laboratory Experiments

Computer-based virtual instrument software is used extensively in the 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 [8]. 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 [9].

A typical control panel in LabVIEW is shown in Figure 1. These control panels have been used very successfully for presentation of data acquisition in laboratory experiments [8, 9], and this usefulness carries over to the Virtual Lab concept, as well as for presentation of computer-generated information. It should be noted that the VL concept is not limited to using LabVIEW software, and other programs are being considered for better simulation of certain dynamics conditions requiring videos or animation.

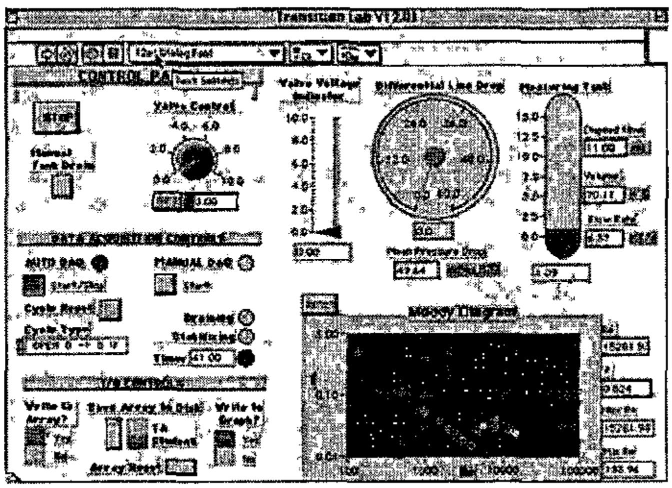

Figure 1: Typical Control Panel for Data Acquisition in an Experimental Lab

Virtual Labs

A Virtual Lab (VL) is created using LabVIEW's graphical programming language ("G") to construct a virtual instrument (vi). Similar to those vi's developed for hardware-based laboratory experiments, the VL's vi consists of a front panel (similar to that pictured in Fig. 1) and a wiring diagram which is the essence of the program. Graphs, indicator buttons, and blocks for data entry can be placed in the front panel in any chosen configuration, and the elements are connected with appropriate "code" in the graphical wiring diagram window. National Instruments provides extensive tutorial documentation with their software package to assist the user in creating these virtual instruments.

To create the VL, the user must run LabVIEW Application Builder. The LabVIEW Application Builder is an add-on package for creating the stand-alone virtual instruments. 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 can be zipped and posted to the course web site. The student can then download the set of files and run the VL at his/her convenience on a computer that does not need to 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 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. This method was employed for the X-Y Plotter VL, and it proved feasible and successful, as all students were able to access, install, and execute the software.

EXPERIMENT

Objectives of the experiment

The system identification experiment, with its corresponding learning objectives, is described in detail in [11]. The experiment focuses on the derivation of a transfer function model of an electromechanical system (x-y recorder) based on data collected at a variety of operating points. As outlined in [11], students gain some experimental experience with frequency response and system identification, learn to draw inferences about system characterization from basic experimental data, use a computer to enhance the model and improve on initial inferences, and confront and explain differences between observed and predicted behavior. When using the virtual lab in conjunction with Layton's experiment, the students gain additional insight into the relationships between the system's parameters and the resultant behavior.

Procedure

Students complete the Rose-Hulman experiment as described in [11], including viewing a video of the actual raw data collection with the x-y recorder at a variety of input frequencies. As in [11], 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 [11], and all materials were provided to the authors by Dr. R. A. Layton of Rose-Hulman Institute of Technology. A sample Excel spreadsheet with results of the optimization highlighted is shown in Fig. 2.

The optimization procedure in Excel relies on the use of a toolbox, where the students specify the cost function to be minimized, and the variables to be determined. The students complete the columns of the Excel worksheet and enter all the necessary equations, however the minimization process is automated, and during the minimization, students do not view the parameter adaptation. Only after the unknown system parameters have been calculated do the students plot the model parameters versus the experimental data to check the validity of the model. Therefore, they do not gain any insight into the effect of any particular parameter on the system response.

CASE 1

Freq (Hz)	Freq (rad)	Vin (V)	length (cm)	Vout (V)	H(w)	Hdb(w)	r	Th. Amp.	Error^2
1.00	6.28	20.00	8.00	20.00	1.00	0.00	0.12	0.02	0.00
2.00	12.57	20.00	8.00	20.00	1.00	0.00	0.25	0.08	0.01
4.00	25.13	20.00	8.00	20.00	1.00	0.00	0.50	0.12	0.02
6.00	37.70	20.00	8.00	20.00	1.00	0.00	0.75	-0.44	0.20
7.00	43.98	20.00	7.70	19.25	0.96	-0.33	0.87	-1.13	0.64
8.00	50.27	20.00	6.50	16.25	0.81	-1.80	0.99	-2.09	0.08
10.00	62.83	20.00	4.40	11.00	0.55	-5.19	1.24	-4.50	0.48
12.00	75.40	20.00	3.30	8.25	0.41	-7.69	1.49	-7.10	0.35
14.00	87.96	20.00	2.50	6.25	0.31	-10.10	1.74	-9.56	0.29
16.00	100.53	20.00	1.90	4.75	0.24	-12.49	1.99	-11.81	0.46
18.00	113.10	20.00	1.60	4.00	0.20	-13.98	2.24	-13.83	0.02
20.00	125.66	20.00	1.25	3.13	0.16	-16.12	2.48	-15.66	0.22
30.00	188.50	20.00	0.60	1.50	0.08	-22.50	3.73	-22.75	0.07
40.00	251.33	20.00	0.40	1.00	0.05	-26.02	4.97	-27.79	3.12

Sum (total error) 5.95

CASE 1 RESULTS

wn	zeta
50.60	0.64

Optimization Results

	Case 1 Min Values	Case 2 Min Values
wn	50.60	46.20
zeta	0.64	0.58
wb	N/A	244.00
error	5.95	0.94

CASE 2

Freq (Hz)	Freq (rad)	Vin (V)	length (cm)	Vout (V)	H(w)	Hdb(w)	r	Th. Amp	Error^2
1.00	6.28	20.00	8.00	20.00	1.00	0.00	0.14	0.05	0.00
2.00	12.57	20.00	8.00	20.00	1.00	0.00	0.27	0.20	0.04
4.00	25.13	20.00	8.00	20.00	1.00	0.00	0.54	0.53	0.28
6.00	37.70	20.00	8.00	20.00	1.00	0.00	0.82	0.07	0.00
7.00	43.98	20.00	7.70	19.25	0.96	-0.33	0.95	-0.75	0.18
8.00	50.27	20.00	6.50	16.25	0.81	-1.80	1.09	-1.93	0.02
10.00	62.83	20.00	4.40	11.00	0.55	-5.19	1.36	-4.79	0.16
12.00	75.40	20.00	3.30	8.25	0.41	-7.69	1.63	-7.63	0.00
14.00	87.96	20.00	2.50	6.25	0.31	-10.10	1.90	-10.18	0.01
16.00	100.53	20.00	1.90	4.75	0.24	-12.49	2.18	-12.40	0.01
18.00	113.10	20.00	1.60	4.00	0.20	-13.98	2.45	-14.34	0.13
20.00	125.66	20.00	1.25	3.13	0.16	-16.12	2.72	-16.05	0.01
30.00	188.50	20.00	0.60	1.50	0.08	-22.50	4.08	-22.24	0.07
40.00	251.33	20.00	0.40	1.00	0.05	-26.02	5.44	-26.19	0.03

Sum (total error) 0.94

CASE 2 RESULTS

wn	zeta	wb
46.20	0.58	244.17

Figure 2. Excel optimization results for Case 1 (second order model) and Case 2 (zero added to numerator). Results of Excel optimization routine are in box at left. Parameters for each model are boxed and highlighted at right.

Knowledge of these relationships is expected after completion of the laboratory exercise, as evidenced by the assessment questions included in the student worksheet, namely worksheet questions 9 and 17, which correspond to the assessment study questions 6 and 13 (Table 1).

Upon completion of the Excel analysis, the students repeat the optimization using brute force via the LabVIEW VL developed by the authors rather than using the optimization toolbox in Excel. With the VL, 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. The VL procedure is listed next:

V L Procedure:

1) Complete the laboratory exercise using Microsoft Excel, as detailed in [11].
2) Download and install the x-y plotter virtual instrument from the web site.
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 (Case 1), adjust the values in the second model (Case 2) to get an even better fit using the same methods.

Virtual Lab Display

Figures 3-5 show the front panel images of the virtual lab. Figure 3 shows the first section of the Virtual Lab. On this screen, students enter frequency (Hz) and response (cm) values based on the worksheet data handed out to the students and displayed on the screen. Completion of data entry results in the automatic population of the four columns at the lower left of the screen (Frequency (rad/s), Voltage out (V), amplification factor, and amplification factor (dB)) and the appearance of experimental data points on the graph at the lower right. Students then adjust the Break Frequency and Static Gain knobs until they feel that they have a good straight-line fit to the data (as displayed on the graph). The static gain should be a multiple of 20 dB/decade and corresponds to the system order, while the break frequency indicates the frequency at which roll-off occurs. As the students adjust these knobs via the computer mouse, the graph updates in real-time, allowing the student to gain insight into the effect of each of these values on the frequency response plot shape.

Figure 4 shows the second screen of the VL. The columns Frequency Ratio, Theoretical Amplitude (dB) and Error Squared are populated automatically by the VL. On this screen, students adjust the horizontal slider bars, changing the values of the natural fequency and damping ration of the

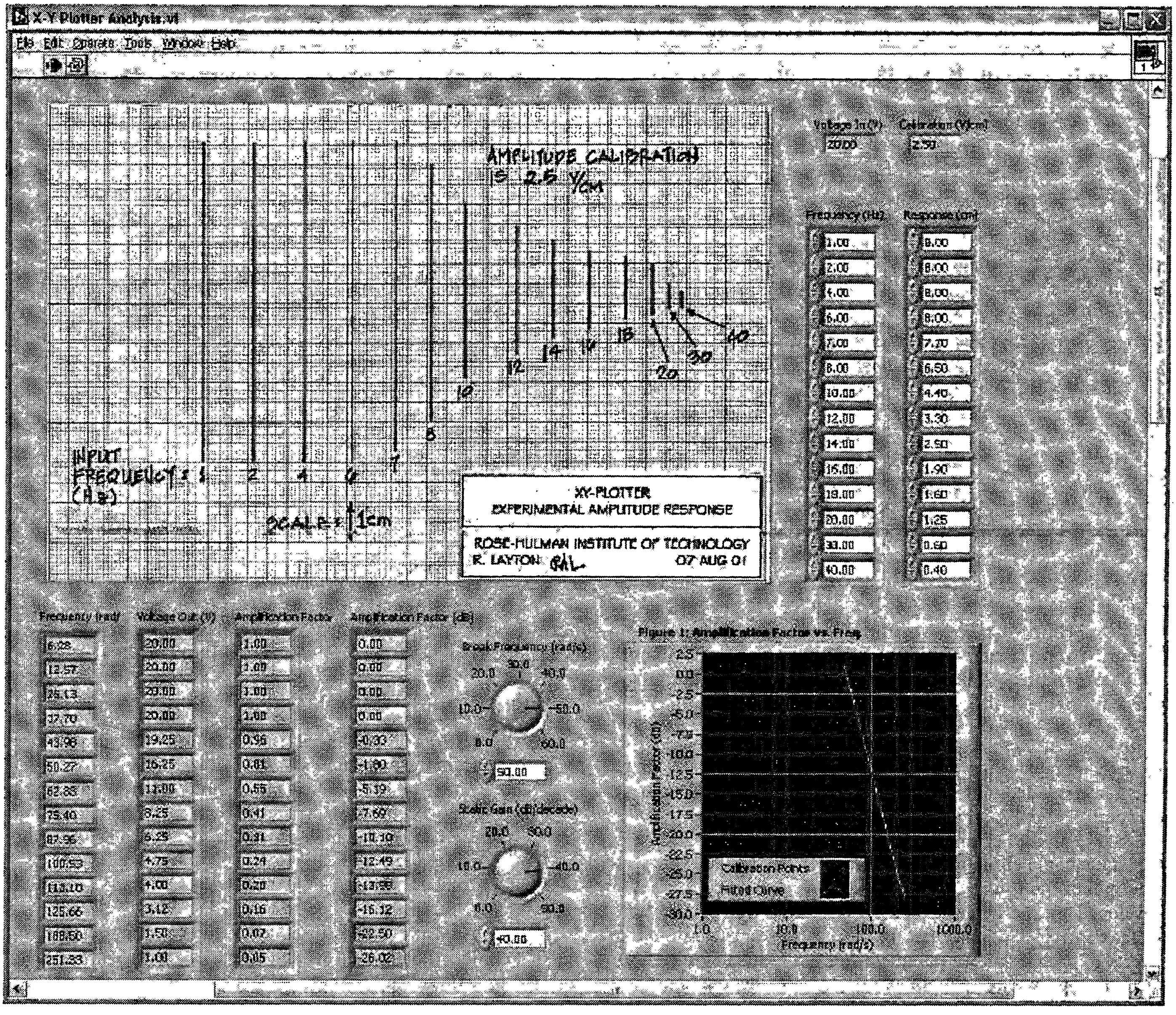

Figure 3. Screen 1 of X-Y Recorder Virtual Lab (VL). Top left inset is data provided to student regarding input frequency, input amplitude, and output of x-y recorder. Top right columns ("Frequency" and "Amplitude") must be entered by the student. Bottom left columns ("Frequency", "Voltage Out", "Amplification Factor" and "Amplification Factor (dB)") automatically populate and data points appear on the graph at bottom left. Students then adjust "Break Frequency" and "Static Gain" knobs until the line on the graph best fits the plotted data points.

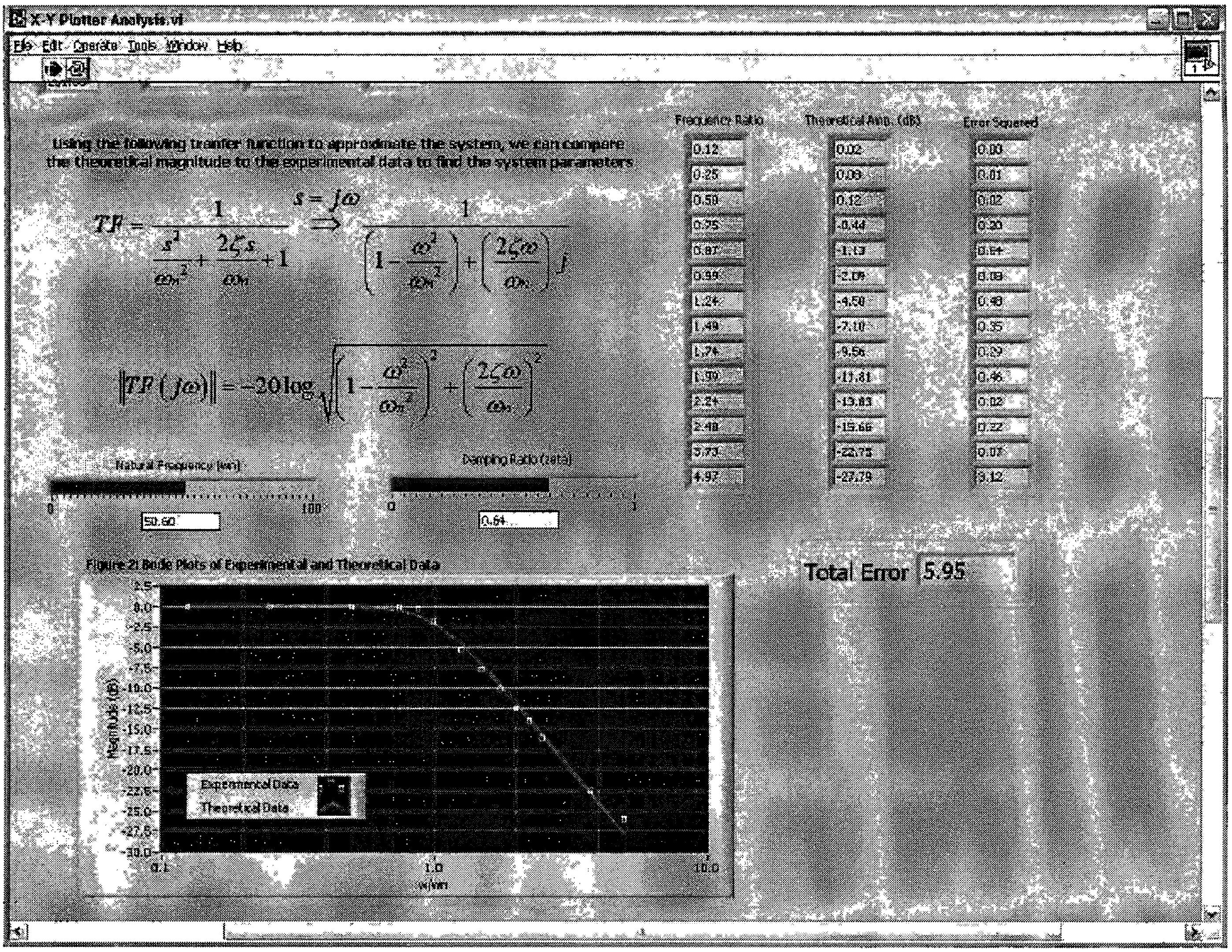

Figure 4. Screen 2 of X-Y Recorder Virtual Lab (VL). This screen encompasses the "Case 1" optimization that was carried out in Microsoft Excel. Data points on the graph automatically appear once Screen 1 data is entered by the student. Then, the student manually adjusts the horizontal slider bars and the theoretical frequency response curve appears in the graph, along with the error calculation between the theoretical curve and the experimental data.

model to get a good fit to the experimental data for Case 1. The "Total Error" box gives them an indication of the quality of the fit, with the goal of minimizing this sum squared error. Again, the graph updates in real time, so that the student can see the effect of natural frequency and damping ratio variation on the theoretical frequency response plot. For example, increasing the natural frequency shifts the point of roll-off to the right, while adjusting the theoretical damping ratio value changes the shape of the curve at the point of roll-off to indicate the presence or absence of amplitude magnification at resonance. The equations for the Case 1 model are presented on this screen.

Figure 5 shows the final screen of the VL, and considers the improved system model. As in the previous screen, the columns are automatically populated and the graph updates in real-time as the students adjust the slider bars for natural frequency, damping ratio, and break frequency. Here, in addition to visualizing the effects of natural frequency and damping ratio on the theoretical frequency response function, students can also witness the effect of the zero in the numerator of the Case 2 model, by noting where the frequency response curve begins to increase due to the presence of the zero.

ASSESSMENT

Upon completion of each phase (Excel and VL) of the exercise, students completed worksheets with a variety of questions, listed in Table 1 at the end of this paper. The responses were used for assessment, described in the following section.

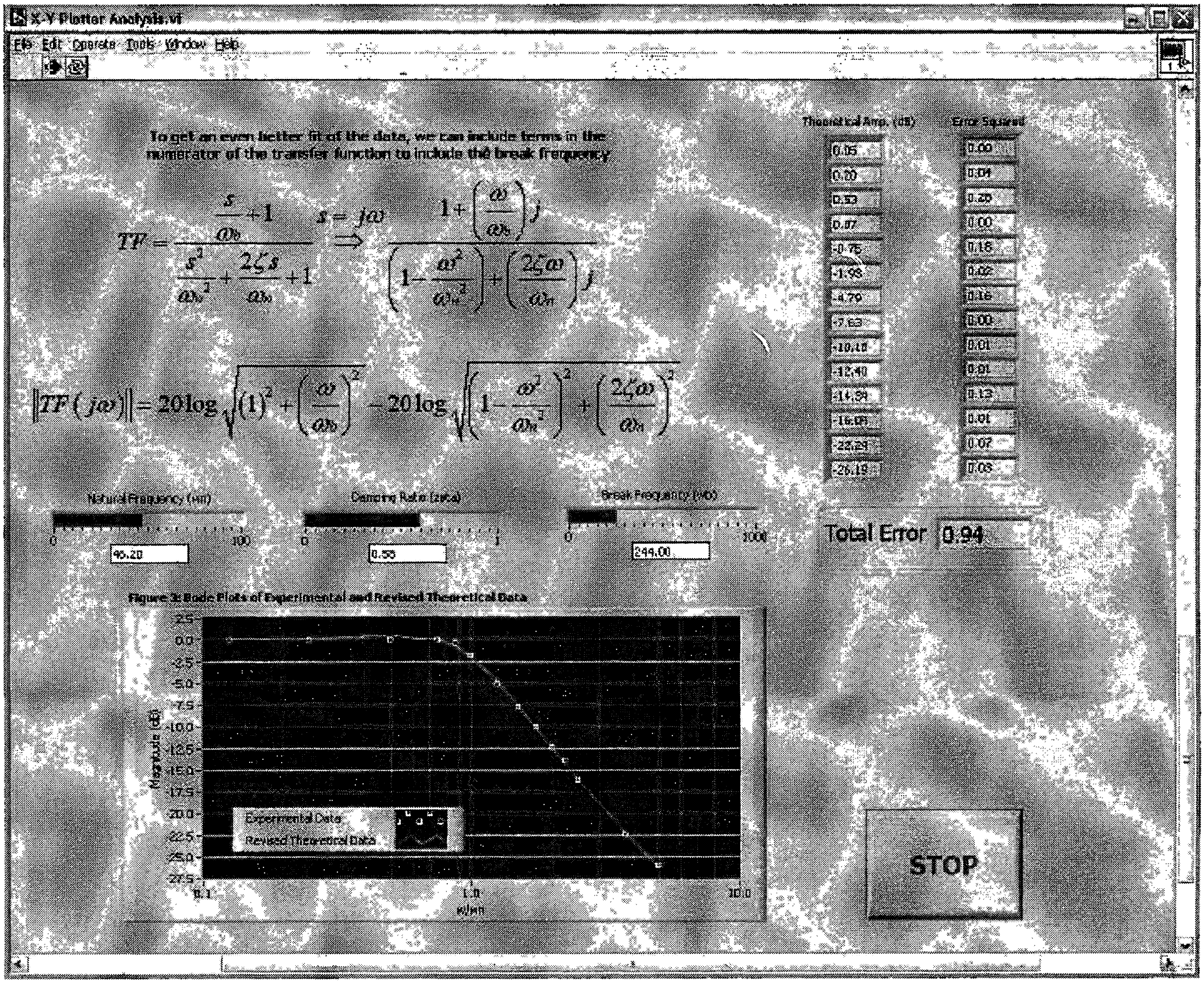

Figure 5. Screen 3 of X-Y Recorder Virtual Lab (VL). This screen encompasses the "Case 2" optimization that was carried out in Microsoft Excel and executes in the same manner as Screen 2

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:

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

None of the 25 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 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

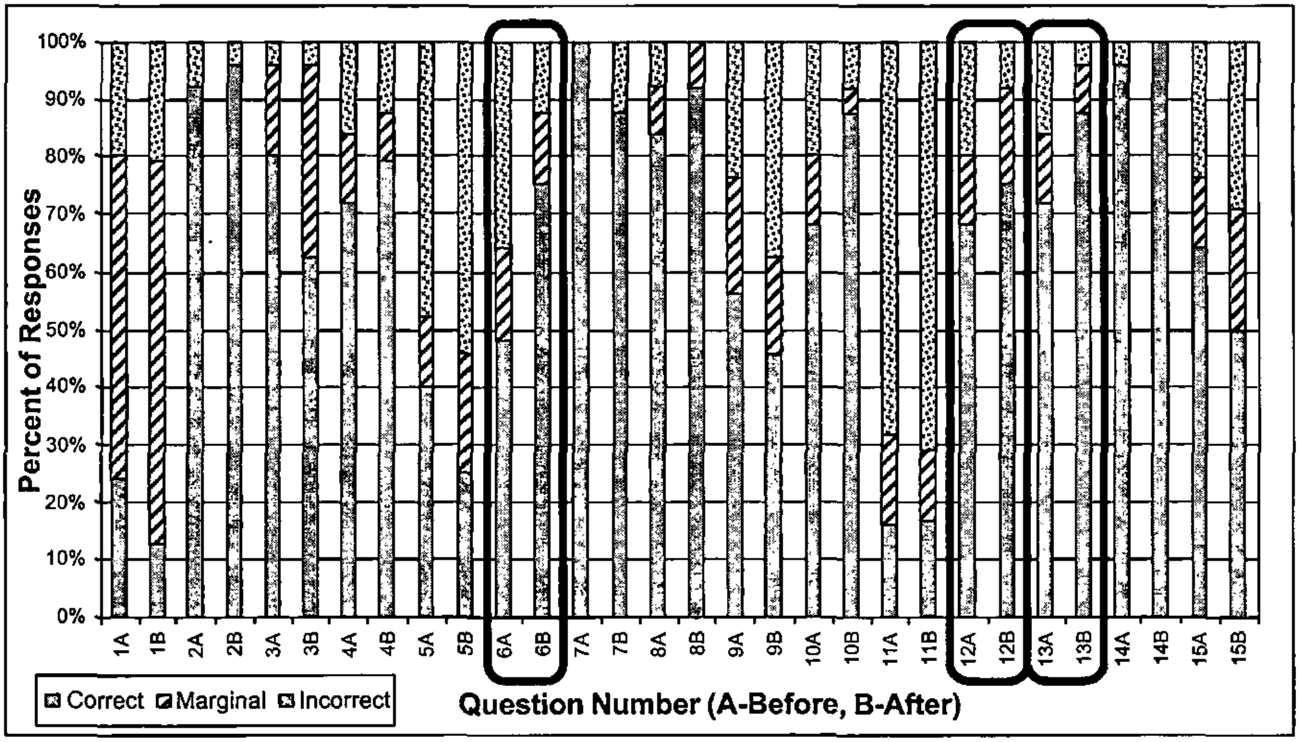

Figure 6. Assessment results for Before and After completion of the VL exercise. Responses were classified as correct, marginal, or incorrect.

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."

A more complete assessment of student learning was conducted based on the responses to the worksheet questions. Students completed worksheet questions after finishing the Excel optimization, and then again after completing the VL exercise. Responses were rated as "correct", "marginal", or "incorrect". Results for this assessment are presented in Fig. 6. Three questions in particular are highlighted for discussion, namely numbers 6, 12, and 13. These study questions corresponded to worksheet questions that asked students to "describe unknown parameters...and how did each parameter affect the frequency response plot", "compare initial and final optimization results...and how the optimization was improved". These questions seek to measure student understanding of the underlying relationships between the *physical system parameters (damping ratio and natural* frequency) and the corresponding frequency response plot characteristics. After students completed the virtual lab, they were more likely to respond correctly to these questions. In fact, the student comments support these findings.

CONCLUSIONS

The Virtual Lab described in this paper was found to improve student understanding of important concepts related to system identification in the frequency domain. Specifically, the VL helped students to visualize in real time the effect of varying system parameters on the frequency response characteristics. The VL was determined to be best used as a supplement to the electromechanical system identification laboratory described by Layton and Grigg [11] that employed Microsoft Excel for parameter estimation based on a least squares minimization fit. The VL has several distinct advantages over the Excel implementation, and the concept of

Virtual Labs could be adopted for other laboratory experiments, or for courses that do not contain supplementary hands-on exercises for the students. Such features include:

- Distribution of the VL as a standalone does not require special software for execution
- Graphs updating in real-time due to student input allow interaction with data for improved understanding of important course concepts

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Table 1. XY Plotter Assessment – Question *Summary.* *Column 1 corresponds to assessment* study number. Column 2 corresponds to the actual question on the student worksheet. Column 3 lists the question asked of the student.

Assess. Question	Worksheet Question	Question content
1	1,2,3	What three characteristics of the class of systems that we've been studying should the basic transfer-function model include? Give initial estimates of each below. These estimates come from the plot that was generated with experimental data.
2	4	Write the initial general expression (no numbers) for the transfer function $TF_1(s)$.
3	5	Some of the parameters in $TF_1(s)$ are known and some are not. List them here:
4	6	Write your expression for the magnitude of $TF_1(?)$ in terms of ? and $r = ?/?_n$
5	8	Compare the theoretical magnitude response based on model TF_1 to the experimentally measured magnitude response. How were they different? Explain why.
6	9	Describe the unknown parameters for this optimization. How did each parameter affect the frequency response plot? Explain.
7	10	What did J_1 characterize? Explain.
8	11	Write the general expression (no numbers) for the transfer function $TF_2(s)$.
9	12	Some of the parameters in $TF_2(s)$ are known and some are not. List them:
10	13	Write your expression for the magnitude of $TF_1(?)$ in terms of ?, $?_b$, and $r = ?/?_n$.
11	15	Compare the theoretical magnitude response based on model TF_2 to the experimentally measured magnitude response. How were they different? Explain why.
12	16	Compare your initial and final optimization results. If your results differed, explain what you did and why to improve optimization of this system. If your initial optimization was accurate, explain why.
13	17	Describe the unknown parameters for this optimization. How did each parameter affect the frequency response plot? Explain.
14	18	What did J_2 characterize? Explain.
15	7, 14	Table 5: Summary of Results.