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Automated Bode-Magnitude and Bode-Phase Frequency Response Testing of Analog Systems and Electronic Circuits Using Standard USB interfaced Test Instruments

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Automated Bode-Magnitude and Bode-Phase Frequency Response Testing of Analog Systems and Electronic Circuits Using Standard USB interfaced Test Instruments

Abstract

This paper describes the design, operation and use of a PC controlled automated frequency response measurement system using the standard USB-interface-enabled bench-top test instruments which are now available in most undergraduate electronics laboratories. Being a much faster alternative to manual measurements, such automated measurements meet a need created by the heavy emphasis put on "design" in the electronics curriculum, in particular, in the design of analog circuits with high precision. TheUSB interfaces built in the instruments are employed in the control of the oscilloscope's settings in a synchronized manner with the frequency and the amplitude settings of the signal generator. The LabView code developed increases the frequency of the signal supplied in steps and acquires the amplitude and the phase data of the signals measured by the oscilloscope at both the input and the output of the circuit under test. It creates a data file compatible with Excel for graphing and data analysis. The code also generates Bode frequency response plots on the screen for the user to observe the response of the circuit as the test progresses. The frequency range of our system extends from 0.001Hz to 25MHz. This wide frequency range makes our system suitable for use in testing the very low frequency response range encountered in Controls and Electro-Mechanical Systems, as well as the medium and high frequency ranges encountered in Vibrations, Acoustics, Ultrasonics, and in Electronics.

1. Introduction

This paper describes the design, operation and use of a PC controlled automated frequency response measurement system using the standard bench-top test equipment available in undergraduate electronics laboratories. Being a much faster alternative to manual measurements, such automated measurements meet a need recently created by the heavy emphasis put on "design" in the electronics curriculum, in particular, in the design of analog circuits with tight design specifications. In the implementation of such high precision circuit designs, it is not possible to hit all of the design specifications with a high degree of precision even though well established design procedures and codes that convert these procedures into a MathCad, Mathematica, MathLab, C file for automated design may have already been developed and used. Ultimately, the design will be put on breadboard and tested against the design specifications. If failing to meet the specifications within their allowed range or "margins", the design has to be redone by either restarting from scratch, or more often, by an iterative method of tweaking on some circuit parameters, and testing the new circuit, and repeating these steps in a series of iterations until all of the targets are hit. The higher the required level of precision in the design specifications the larger the number of the iterations needed, therefore forcing a quick turn around time for testing in order to fit such design experiments into the limited hours of a weekly laboratory schedule.

2. The Measurement System

The automated frequency measurement system reported here employs a standard set of bench-top instruments consisting of a Tektronix Digitizing Oscilloscope (Model TDS2024C) and a Tektronix Arbitrary Function Generator (AFG3021C). Both of these new generation instruments come equipped with USB interfaces. The desktop computer is equipped with LabView-2013. A system schematic of the measurement setup is given in Figure 1. The same setup equipped with a USB interfaced DMM (DMM4040 or similar) can also be employed for the automated measurement of I-V and C-V characteristics of semiconductor devices and sensors, and to extract SPICE parameters from them as reported earlier. (See References [1] and [3])

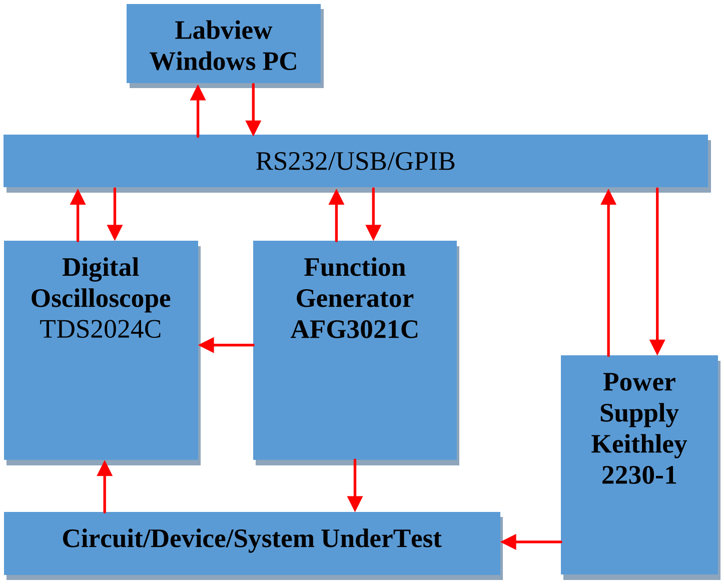


Figure 1. The CIE-Bode Automated Frequency Response Test Setup

In the frequency response measurements of a circuit magnitudes and the relative phase of a signal applied to the input and the voltage appearing at its output of a circuit have to be measured. To measure a frequency response, the signal frequency has to be stepped, the measurement being repeated at every step to gather data points to plot the response as a function of the frequency. In principle the input and output voltage amplitude measurements can be accomplished very simply by employing two AC voltmeters. However, most undergraduate teaching laboratories are equipped with only one meter per station. Besides, most DMMs have a very limited frequency range, typically less than 100 KHz. Beams[2] has shown that, with external circuitry controlled by a PC, one can multiplex the input and the output signals into a single voltmeter. He employed an I-Q phase detector and incorporated it with a multiplexer to do both phase and amplitude measurement with only one digital multimeter. However, the frequency was limited by the phase detector to only two decades of dynamic range and by the multimeter to a maximum value of 100 KHz.

In our system, like in the earlier version we had reported about [5], we employ multiple channels of a digital oscilloscope rather than a multimeter. The following is a list of the advantages of our system over the ones employing multimeters. Unlike the digital multimeter, the oscilloscope, (1) provides multiple channels, thus eliminating the need for multiplexing, (2) has many orders of magnitude higher frequency bandwidth and covers DC through 200MHz, (3) displays actual waveforms, showing distortions, noise and oscillations in real time without hiding or averaging them into the signal's amplitude, and (4) can be triggered from a reference channel or externally for accurate time delay (phase) measurements in between the channels. In addition, from the waveforms displayed one can measure and verify the frequency of the signal generator's output.

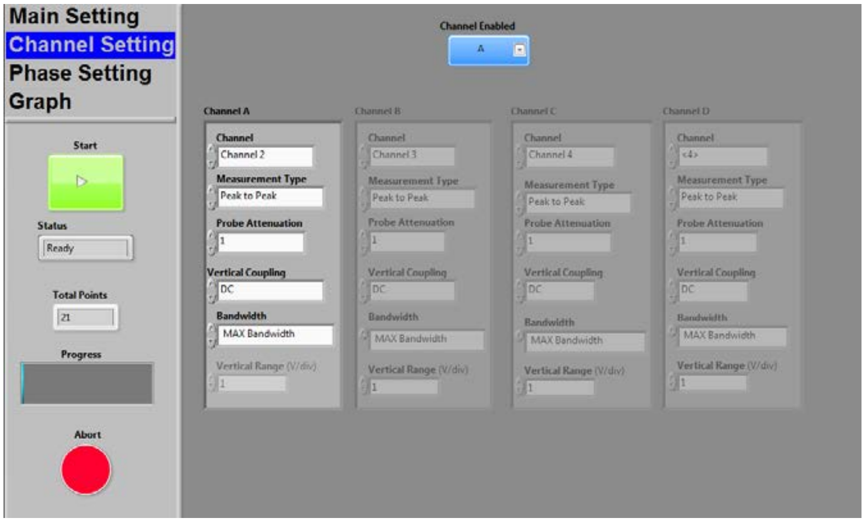
For our "CIE-Bode" Labview program to work properly the oscilloscope's first two channels should be connected to the input and output terminals of the circuit under test. Measurement of the input is needed to calculate the absolute value of the Gain or Loss. It also eliminates the possibility of erroneous and distorted frequency response plots which are caused by the frequency dependent loading and the drift in the signal generator's output. These erroneous and distorted frequency response measurements are commonly encountered in undergraduate laboratories where the inexperienced student assumes the amplitude shown/set on the signal generator's display is the same as the actual signal produced at the output of the instrument. In reality the displayed value is the amplitude the generator would produce if it is connected to a load with 50 ohms resistance, matching the 50 ohms internal (Thevenin equivalent) resistance of the generator. In most cases this condition is not met. With load resistances higher than 50 ohms, the signal's amplitude can be as high as double the value displayed on its panel. For this reason it is important to have one channel dedicated to measuring the signal actually applied at the input of the circuit at each and every step of frequency during the test. An oscilloscope with a minimum of two channels, one connected to the input, the other connected to the output is needed.

Our program allows up to four channels to be recorded, one input and up to three outputs. Any of these four channels can be chosen as the trigger source. However, external triggering from the signal generator's SYNC output is recommended since it produces constant amplitude (TTL level) square pulses with fast transitions to create precisely defined trigger timing. It is prudent and recommended practice that an automated measurement be preceeded by a manual setting of the instruments in which (1) the signal generator's frequency is brought to the starting frequency of the measurement, (2) its output is adjusted to the required level, (3) the connections mentioned are made, (4) the oscilloscope's settings (AC/DC coupling, Y- sensitivities, time base, trigger type (external, normal, not auto) and the trigger level are all adjusted so that steady waveforms are obtained with a few whole cycles of the waveform filling the screen without being clipped. This procedure, by freeing the program from a potentially long scaling/rescaling procedure, saves time and guarantees a successful measurement.

Our CIE-Bode Labview program initially displays the graphic interface screen shown in Figure 2a for the user to pick instrument settings and specify the range of the frequency sweep, "Start Frequency", "Stop Frequency", and "Points per Decade". The default frequency increment scale is "Logarithmic" which is the standard for Bode plots. However, it can be changed to "Linear" increment option if preferred (for narrow band resonant devices and filters). The program checks all the instruments interfaced to the PC and allows the user to pick any Signal Generator-Oscilloscope pair. Although USB is the default interface, the program can detect and work with RS 232 or GPIB interfaced instruments as long has the system and the PC are set up with proper adapters (like GPIB-to-USB) and their drivers. After the initial settings are done the program allows the user to select options for individual channel settings like AC/DC coupling, probe attenuation, trigger source, etc., in the "Channel Setting" mode as displayed on the upper left corner. Note that up to four channels can be used (the oscilloscope has four channels) to measure the frequency response of the system at different points of the circuit/system under test. Unused channels can be disabled for faster tests and smaller data files. Phase measurements are optional; the default setting skips the phase measurements option for speedier frequency response tests. The "Phase Setting" window allows up to four pairs of channel phase differences to be measured, recorded and plotted, simultaneously. (See Figure 2c.)

Status: Ready
Total Points: 21
Function Generator I/O: AFG
Oscilloscope I/O: Scope
Voltage Division: Auto V/div
Waveform Function: Sine
Input Voltage(Vpp): 1
Start Frequency: 10 Hz
Stop Frequency: 1000 Hz
Trigger Source: Channel 1
Trigger Coupling: AC
Trigger Level(V): 0
Increment Scale: Log
Frequency Step(Hz): 10
Points Per Decade: 10

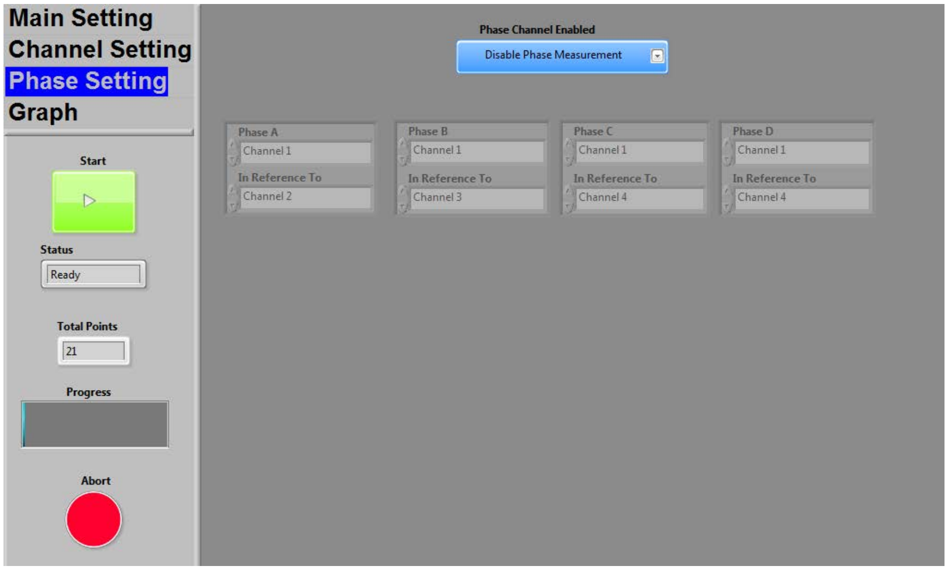
Figure 2a. The CIE-Bode Graphical User Interface for Initial Setup and Measurement Options



Status: Ready
Total Points: 21
Channel Enabled: A

	Channel A	Channel B	Channel C	Channel D
Channel	Channel 2	Channel 3	Channel 4	<4>
Measurement Type	Peak to Peak	Peak to Peak	Peak to Peak	Peak to Peak
Probe Attenuation	1	1	1	1
Vertical Coupling	DC	DC	DC	DC
Bandwidth	MAX Bandwidth	MAX Bandwidth	MAX Bandwidth	MAX Bandwidth
Vertical Range (V/div)	1	1	1	1

Figure 2b. The CIE-Bode Graphical User Interface for Channel Settings



Phase Channel Enabled: Disable Phase Measurement

Status: Ready

Total Points: 21

Phase A: Channel 1, In Reference To: Channel 2

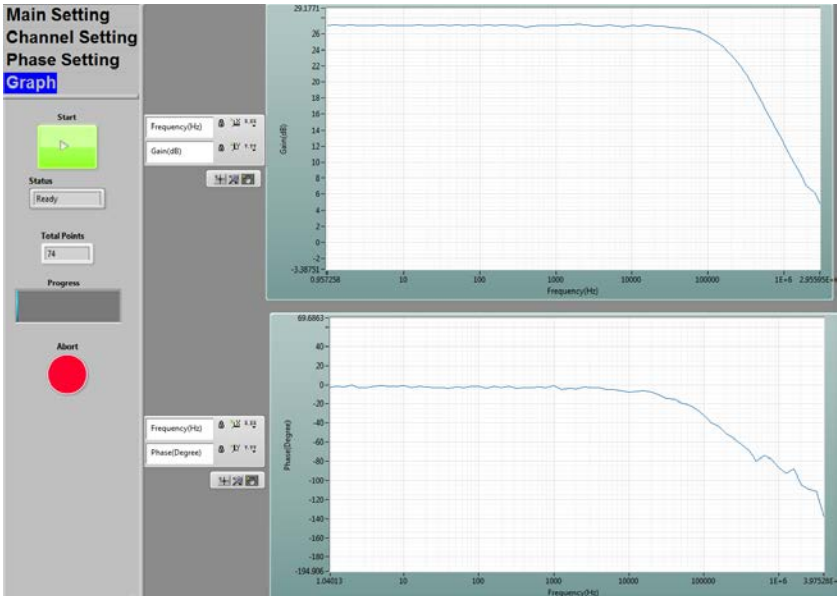
Phase B: Channel 1, In Reference To: Channel 3

Phase C: Channel 1, In Reference To: Channel 4

Phase D: Channel 1, In Reference To: Channel 4

Figure 2c. The CIE-Bode Graphical User Interface for Optional Phase Measurement Settings

When started the CIE-Bode Labview program switches to “Graph” mode and displays Bode Magnitute and Bode Phase plots and updates the data points as the frequency stepping and measurements continue. It also displays the total number of frequency steps to be completed and shows the progress of the test by displaying percentage completed in a horizontal bar graph window titled “Progress”. Figure 3 below shows the screen copy of the resulting Bode plots (both Magnitude and Phase measured) as displayed on the screen at the end of a frequency response test performed on a student designed OpAmp amplifier circuit.



Status: Ready

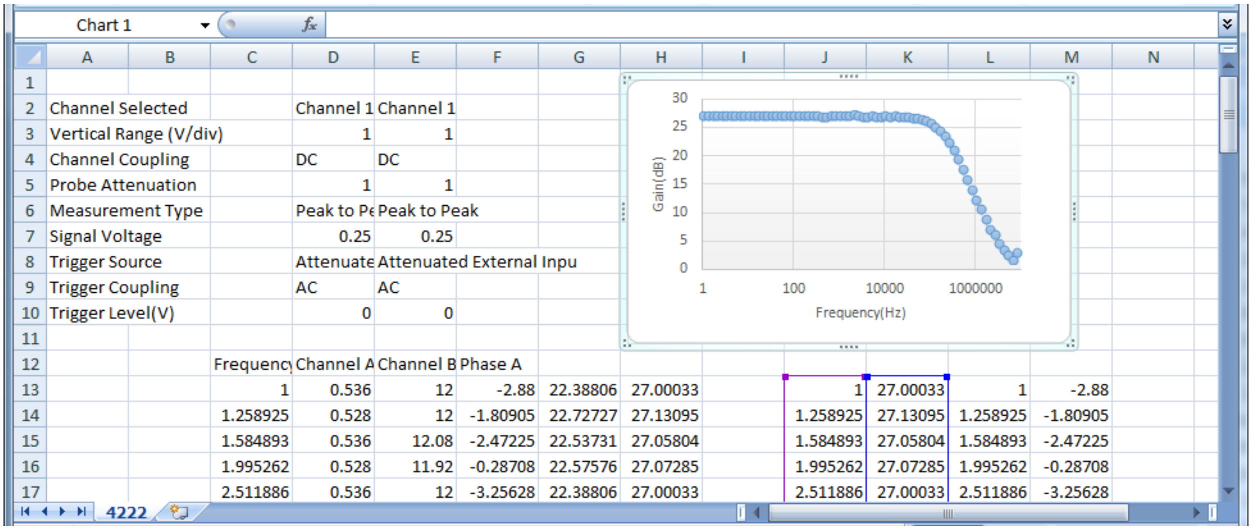
Total Points: 74

Figure 3. The CIE-Bode Graphical User Interface for On-Screen Monitoring of Frequency Response Tests (Shown is a Test Completed on a Student Designed OpAmp Amplifier.)

The graphical display of the frequency response is auto-scaled and renewed after each and every new data point is acquired. The numerical values of the frequency measured and the gain value (in dB's) calculated from the last (the current) measurement are also displayed in the numerical display boxes on the left of the graphs as the test progresses.

The Labview CIE-Bode program calculates the spot values of the frequency at the current step by using logarithmic increments corresponding to the "Points/Decade" value entered by the user. This assures evenly distributed data points on the Bode magnitude or Bode phase plots. For each and every frequency step, input and output waveforms are displayed on the oscilloscope screen. In order to avoid imprecise or erroneous data collection, which are typically caused either by too small a vertical deflection on the screen or the clipping of the waveform due to overranging of the A/D converter, the Labview CIE program uses an algorithm to scale the vertical sensitivity up or down to keep the waveform within a range of 20% to 80% of the screen. Similarly, for the accurate measurement of the zero-crossing points of the waveforms, which are needed for delay and phase calculations, the horizontal span of the screen (10bits) should fit a few whole cycles but not too many. The Labview CIE program has an algorithm to set the time scale of the oscilloscope to fit 3 to 5 full cycles of the waveforms. This routine employs the current value of the frequency to calculate and pick the right horizontal scale on the oscilloscope. If the program cannot fit the waveforms into one screen after 10 attempts, it pauses and asks for manual interference.

The CIE-Bode program, in addition to displaying the Bode plots on the screen, creates a data file in comma delimited text format and saves all the channel settings and measured channel data in it. This allows the user to import the data into Excel, and process it, analyze it and plot it later. Figure 4 shows an Excel window displaying the contents of the data file and the graph it generated based on the test run given in Figure 3.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	Channel Selected			Channel 1	Channel 1								
3	Vertical Range (V/div)			1	1								
4	Channel Coupling			DC	DC								
5	Probe Attenuation			1	1								
6	Measurement Type			Peak to Pe	Peak to Peak								
7	Signal Voltage			0.25	0.25								
8	Trigger Source			Attenuate	Attenuated External Inpu								
9	Trigger Coupling			AC	AC								
10	Trigger Level(V)			0	0								
11													
12			Frequenc	Channel A	Channel B	Phase A							
13			1	0.536	12	-2.88	22.38806	27.00033		1	27.00033	1	-2.88
14			1.258925	0.528	12	-1.80905	22.72727	27.13095		1.258925	27.13095	1.258925	-1.80905
15			1.584893	0.536	12.08	-2.47225	22.53731	27.05804		1.584893	27.05804	1.584893	-2.47225
16			1.995262	0.528	11.92	-0.28708	22.57576	27.07285		1.995262	27.07285	1.995262	-0.28708
17			2.511886	0.536	12	-3.25628	22.38806	27.00033		2.511886	27.00033	2.511886	-3.25628

Figure 4. The Excel Output File with Data Generated During the Test in Figure 3

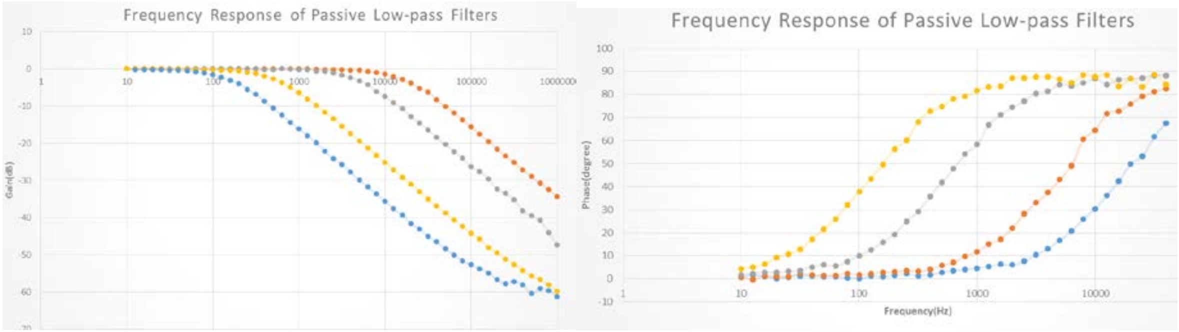


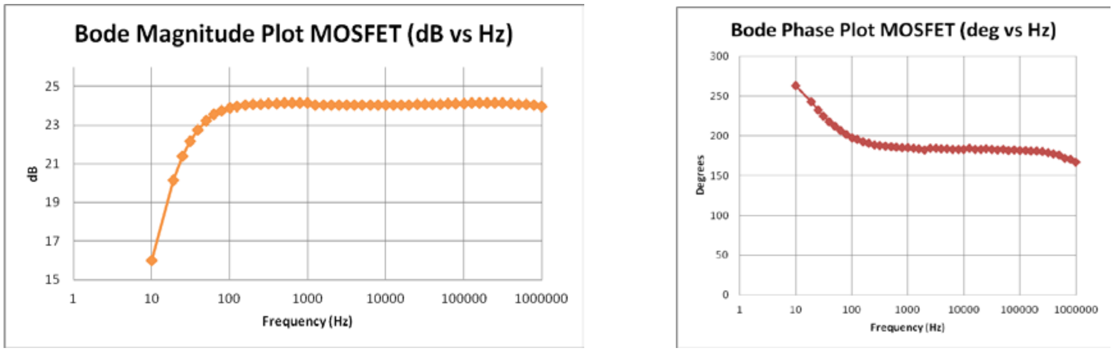
Figure 5. Bode-Magnitude (left) and Bode-Phase (right) Frequency Response Plots of Various R-C Low-Pass Filters Graphed from the Test Data Saved in Excel

3. Frequency Response Samples, Results and Discussion

The automated frequency response measurement system described hereto has been used in the characterization of various active/passive filter circuits and in verifying frequency responses of various amplifier circuits students are expected to design and verify in the junior electronics laboratory at the University of Southern Maine. Students design BJT, JFET, MOSFET and OpAmp amplifiers to meet a given set of design specifications including mid-band gain, cut-off frequencies and bandwidth. Each “Group” (a team of two students) is assigned a different numerical set of design specifications. (Example: BJT Amplifier Gain Spec = 75 + 15x Group Number = 165 for the Group No. 6, = 90 for the Group No.1). These amplifiers are designed from scratch. Students are required to record their design procedure and do their design calculation in a “Mathematica” file they create. The design is first verified by simulating its circuit and testing it for compliance with the design specifications assigned to their group. Once SPICE verified, the amplifier circuits are built on proto boards, debugged and tested. The new LabView based “CIE-Bode” reported here has become the primary tool in testing the amplifier circuits built in the laboratory. Students test and verify compliance of their design with the Gain and Bandwidth specifications assigned to them within a short laboratory session and have enough time to go over several iterations of design-build-test within one laboratory period if the first design fails to meet the design specifications.

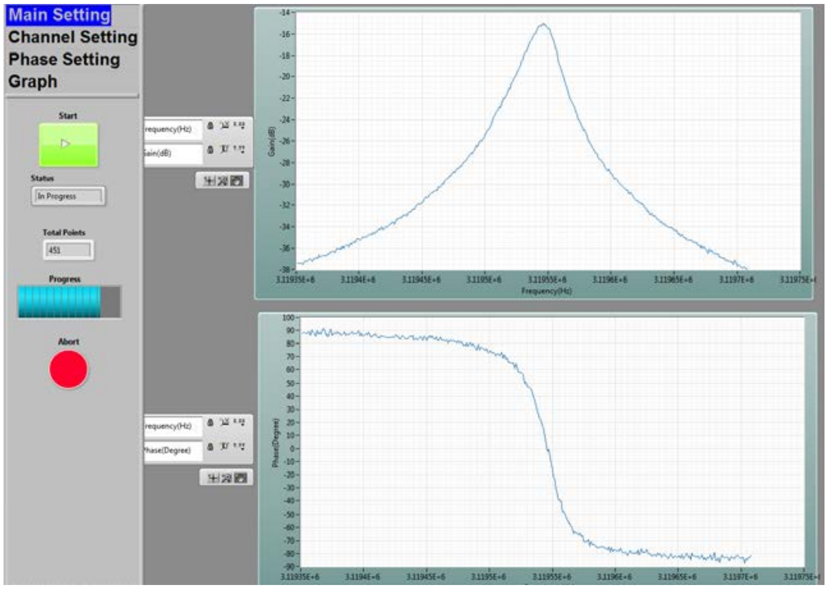
Figures 3 through 8 give the results of such automated frequency response tests. Shown in Figure 6 are the Bode Magnitude and Bode Phase test results obtained from such automated tests performed on a MOSFET amplifier circuit designed and verified by a student in the ELE 346 Electronics II class lab. The design specs were,

Amplifier Gain = 15 ± 10% (or = 23.5dB ± 1dB) and Cut-off Frequency, $f_{-3dB} \leq 100$ Hz, both of which were satisfied by this student’s design, as seen from the plots given in Figures 6a and 6b.



Figures 6a & 6b. Bode Magnitude and Phase Plots of Freq Response Data Saved from a MOSFET Amplifier Designed and Tested in ELE 346 Electronics (a sample of student work)

High resolution of the signal generator available in our labs (Tektronix AFG3024C with a frequency resolution of 1/10,000,000) makes our system excel in the frequency response testing of very narrow band Quartz Crystal Band-Pass or Band-Reject filters. Figures 7a & 7b show the frequency response of a Quartz Crystal Band-Pass filter with a center frequency of 3.119 MHz. Note that, in the wider band tests shown in Figures 3-6 where the frequency spans several orders of magnitude a logarithmic frequency scale was employed, therefore, the frequency values were stepped in non-uniform steps calculated to create points uniformly spaced on a logarithmic scale. In the narrow band-pass filter measurents shown in Figures 7a and 7b , however, a linear scale and steps equal in increments was preferred. Note that our CIE-Bode system easily detected the pass-band peak and revealed the details of a very narrow -3dB bandwidth of 28 Hz around the center frequency of 3,119,540 Hz. This unusual performance and resolution is comparable to expensive spectrum/network analyzers and proves that our system can serve as a low cost alternative.



Figures 7a & 7b. Bode Magnitude and Phase Plots of Freq Response of a Very Narrow Band Quartz Crystal Band-Pass Filter

In Figure 8 frequency response measurement results taken with a 10X step-up resonant transformer are shown in a Bode Magnitude plot format (dB voltage ratio vs. log of frequency). Note that this device has a narrow range of flat frequency response followed by a steep resonance peak, typical of the I.F. (Intermediate Frequency) transformers employed in the I.F. amplifiers of superheterodyne radio receiver.

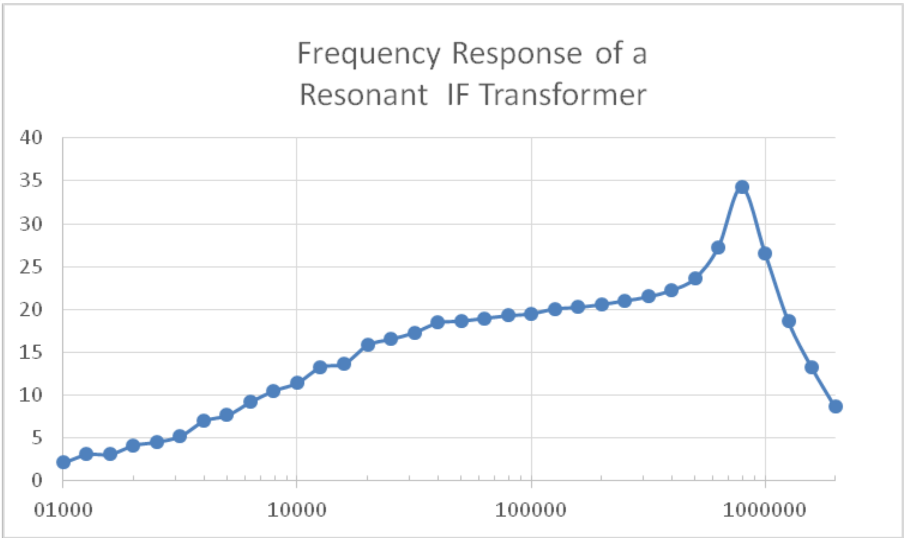


Figure 8. Bode Magnitude Plot of Freq Response of a Resonant I.F. Transformer

Last example given in Figure 9 represents frequency response of an acoustically coupled pair of loudspeakers, one acting as a microphone. The resonant frequency of this electro-acoustic system is clearly dominant at 200 Hz but a higher frequency mode (6,300 Hz) is also highly visible. Note that our CIE-Bode system is capable of detecting and displaying the resonant modes of vibration of a mechanical system, an important application in electro-mechanical systems and vibration testing. It also displays a very large dynamic range of 60 dB's as seen in Figure 9.

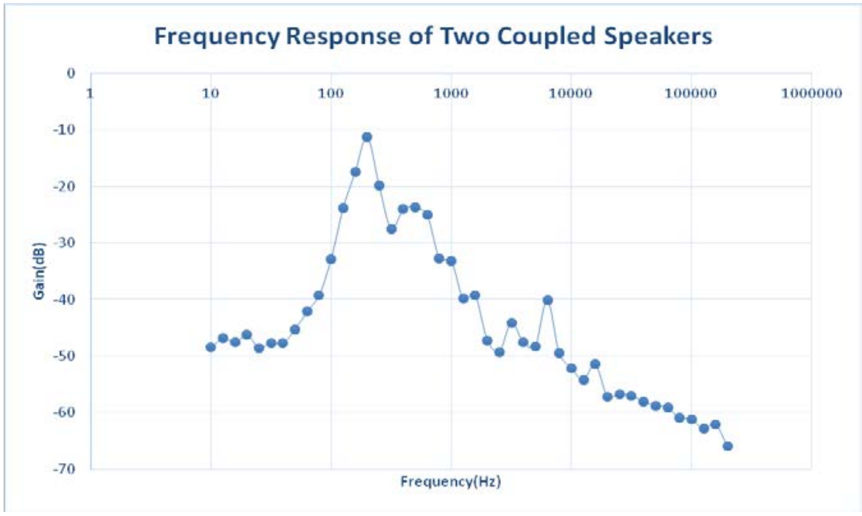


Figure 9. Bode Magnitude Plot of the Freq Response of an Acoustically Coupled Pair of Loudspeakers

3. Conclusions, Remarks, Student Involvement and User Response

The system was built and the LabView programming was written as a part of a faculty-directed senior design project at the University of Southern Maine. One highly motivated electrical engineering student (the co-author) worked on the project, focusing on learning LabView programming and developing the code. The project had the goal of creating a GUI version of an earlier frequency response test code written in Java while taking advantage of the features of the new USB interfaced instruments purchased for our Computer-Integrated-Electronics (C.I.E.) Laboratory. The new CIE-Bode code was developed and beta tested while the instructional laboratory work was being conducted. Therefore, beta testing of it with student users could be done and comments and feedback could be collected for improvement on the go.
For the past two semesters the CIE-Bode setup has been used in the characterization of the frequency response of single- and multi-stage amplifiers, operational amplifier circuits, passive- and active-filters all designed and tested in the junior year Electronics I & II laboratories at the University of Southern Maine.

One important feature of the CIE-Bode code is its portability. A run time executable copy can be created which can be installed and run on standard Windows based PC's and laptops or tablets, or can be distributed to all computers in a computer-integrated electronics or mechanical engineering laboratory without requiring LabView to be installed on each and every computer.

It should be noted that the set-up and the code developed can easily be adapted to measuring the frequency response of electromechanical and non-electrical (such as acoustical) systems with the addition of appropriate transducers and sensors. One important application would be to determine the vibration mode frequencies of mechanical structures and testing, tuning and repair of musical instruments. In addition, it can be used in the design of systems and do vibrational analysis on them similar to the one explained by Walsh and Orabi [4].

This version of the "CIE-Bode" has been test run as a replacement to our earlier version which was written in Java and which had limited GUI. The CIE-Bode was made available to our Junior Electronics students as an optional alternative to the older Java version with which they were familiar with from the previous semester's laboratory work. After trying the new LabView GUI based version they did not use the older version, at all.

Responses to a question asking whether they prefer to use the new "CIE-Bode" or not, 19 out of 23 responded with 4 points out of 4, 2 responded with 3 points out of 4 and 2 did not return the questionnaire. The new GUI based "CIE-Bode" will be the default automated test tool in all Electronics labs from now on. It will also be available to support Controls, Vibrations, and Acoustics courses and their laboratory experiments in the Engineering Department.

After the publication of this paper the authors plan to make copies of the run time version available to the public upon request.

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