2006-1813: PROJECT TUNA II - BODE ANALYZER AND TEACHING TOOL

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Project TUNA II –Bode Analyzer and Teaching Tool

Abstract

Students measuring the frequency response of a linear circuit (e.g., an active filter) by manual methods find the task mind-numbing and repetitive, and the purpose was frequently lost in the minutiae of data-taking. Project TUNA (Texas Universal Network Analyzer), a Bode analyzer for low to moderate frequencies, was conceived as an answer to this problem. The prototype of Project TUNA was developed as a project in Electronics II (EENG 4409) in 1999, and permanent copies were constructed in 2000. Project TUNA has been integrated into the electronics curriculum of UT-Tyler since that time. It is used as both a laboratory instrument and as a teaching tool, particularly to illustrate the principles of phase-sensitive demodulation.

However, Project TUNA had drawbacks. The performance of its switching-type phase-sensitive demodulator degraded markedly above 100kHz. The dynamic range of voltage gains was limited (±30dB), and analysis times were longer than necessary for frequencies above a few hundred Hz. Project TUNA also required three GPIB-controlled test instruments (power supply, function generator, and multimeter).

These limitations provided the impetus for Project TUNA II. Project TUNA II has much-improved performance: wider dynamic range (±40dB), wider frequency range (10Hz to 1MHz), and shortened analysis times for frequencies above 200Hz. Use of a multifunction data-acquisition card in the host PC eliminated the GPIB-controlled power supply and dc voltmeter; only a GPIB-controlled function generator is required. Project TUNA II was developed in prototype form in 2001; permanent hardware and a much-improved LabVIEW virtual instrument were created in 2004. Project TUNA II is currently used alongside Project TUNA in electronics laboratories, and Project TUNA II is used to expand the instructional themes of the original Project TUNA. This paper describes the development, design, laboratory use, and instructional resources of Project TUNA II.

Description of prior work—overview of Project TUNA

The junior-year curriculum of the BSEE program of the University of Texas at Tyler includes two semesters of electronics laboratory courses. Measurement of frequency response of linear networks is a part of the laboratory procedures of each semester. In particular, extensive measurements of complex (magnitude and phase) frequency response are made in a laboratory procedure on active filters in EENG 4109 (Electronic Circuit Analysis II Laboratory). Students performing these measurements by manual methods found the task mind-numbingly repetitive, and the purpose of the laboratory was frequently lost in the minutiae of data-taking. Project TUNA (Texas Universal Network Analyzer), a Bode analyzer for low to moderate frequencies, was conceived as an answer to this problem. Project TUNA, combining custom external hardware, GPIB instrumentation, and a LabVIEW virtual instrument program, was designed and developed in prototype form as a class project in EENG 4109 in 1999. Permanent copies of the Project TUNA hardware were constructed in 2000. Project TUNA has been used in the laboratory curriculum since that time.

A block diagram of Project TUNA is shown in Fig. 1.

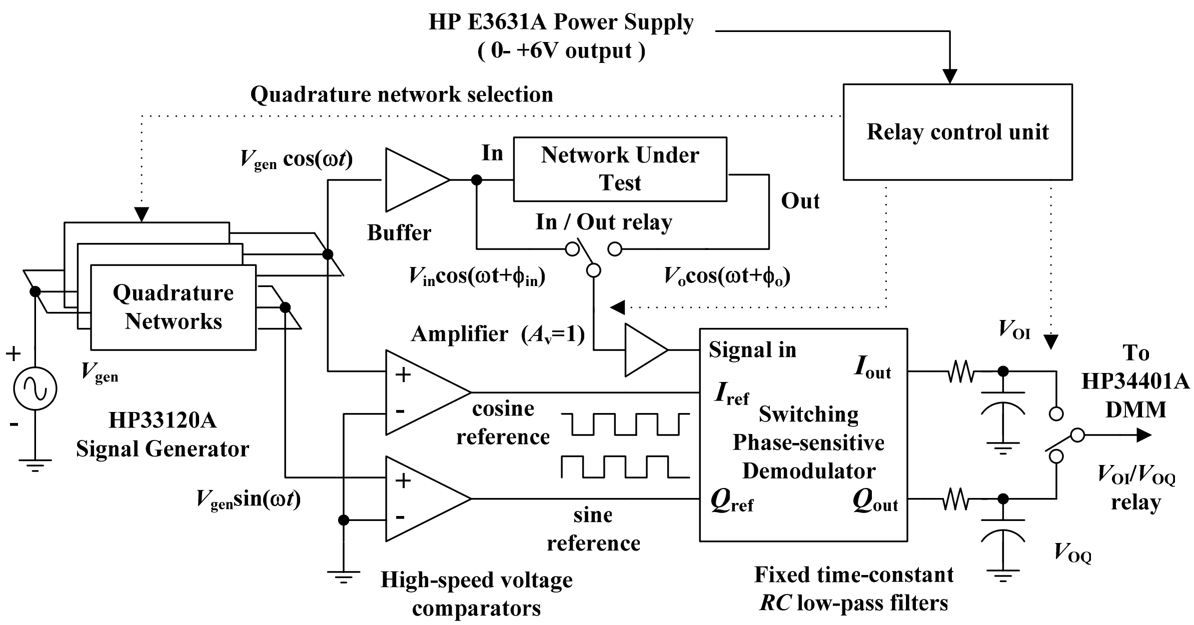

Fig. 1. Block diagram of Project TUNA

Project TUNA relies upon switching phase-sensitive demodulation to measure both the magnitude and phase of the input voltage V_{in} and output voltage V_o of the network under test. An Agilent HP33120A arbitrary waveform generator furnishes a sinusoidal signal to three unity-gain quadrature networks. Each quadrature network contains four two-pole unity-gain all-pass filters arranged in two groups as shown in Fig. 2 below. The poles of the filters are chosen using a design method described by Keely[1] such that the phase difference between the two output voltages remains constant at 90° over a wide range (approximately 25:1) of frequencies. Three quadrature networks are used to cover the range of frequencies from 10Hz to 100kHz; the appropriate quadrature network is selected by activating its relay.

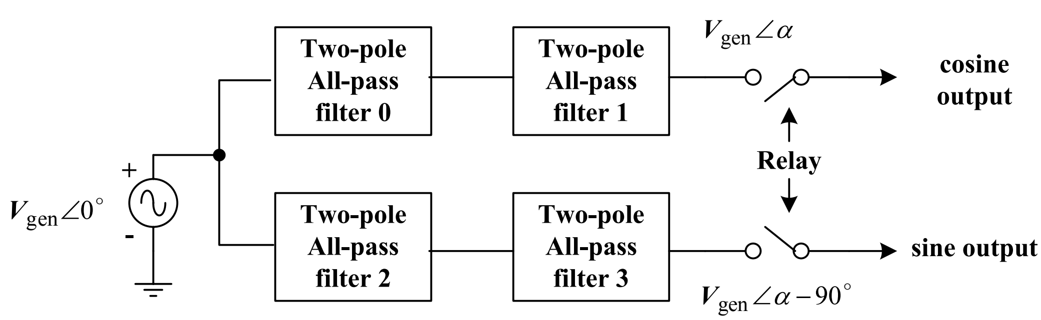

Fig. 2. Block diagram of the Project TUNA quadrature network.

The cosine output voltage is applied to a buffer amplifier that drives the input of the network under test; the cosine output voltage is therefore the reference signal for measurements of phase of the network under test. Both the cosine and sine outputs pass through high-speed voltage comparators (LM361) that produce quadrature square waves in that are the controlling signals for the switching phase-sensitive demodulator. Low-pass filters extract the dc components V_{OI} and V_{OQ} of the voltages at outputs I_{out} and Q_{out} of the switching phase-sensitive demodulator. A relay allows V_{OI} and V_{OQ} to be read sequentially by the HP34401A multimeter.

The magnitude V_{in} and phase φ_{in} (relative to the cosine output voltage) of the voltage at the input of the network under test are determined from V_{OI} and V_{OQ} with the input of the phase-sensitive demodulator connected to the input of the network under test. The relationships (computed by the LabVIEW Project TUNA virtual instrument) are:

$$V_{in} = \pi \cdot \sqrt{(V_{OI\,in})^2 + (V_{OQ\,in})^2} \qquad (1a)$$

$$\phi_{in} = \tan^{-1}\left(\frac{-V_{OQ\,in}}{V_{OI\,in}}\right) \qquad (1b)$$

where the "in" subscripts of V_{OI} and V_{OQ} denote their measurement with the phase-sensitive demodulator connected to the input of the network under test. Similarly, the magnitude V_o and phase φ_o of the output voltage of the network under test are determined from V_{OI} and V_{OQ} with the output voltage of the network under test connected to the input of the phase-sensitive demodulator. The relationships are:

$$V_o = \pi \cdot \sqrt{(V_{OI\,o})^2 + (V_{OQ\,o})^2} \qquad (2a)$$

$$\phi_o = \tan^{-1}\left(\frac{-V_{OQ\,o}}{V_{OI\,o}}\right) \qquad (2b)$$

where the subscript "o" denotes the phase-sensitive demodulator's input being connected to the output of the network under test. A relay accomplishes this switching.

The LabVIEW virtual instrument displays voltage gain (ratio of V_o to V_{in}) over a range of –30 to +30dB and phase (ϕ_o–ϕ_{in}) from –180° to +180°.

Relays play a prominent role in the operation of Project TUNA. Activation of the relays under control of LabVIEW was made difficult due to a lack of directly-addressable digital I/O ports. The relay control unit of Fig. 1 allowed the relays of Project TUNA to be controlled with an analog voltage produced by the 0– +6V output of the HP E3631A dc power supply. Figure 3 below is a block diagram of the relay control unit. (The relay control unit provides four outputs for switching quadrature networks, although only three were eventually used with Project TUNA).

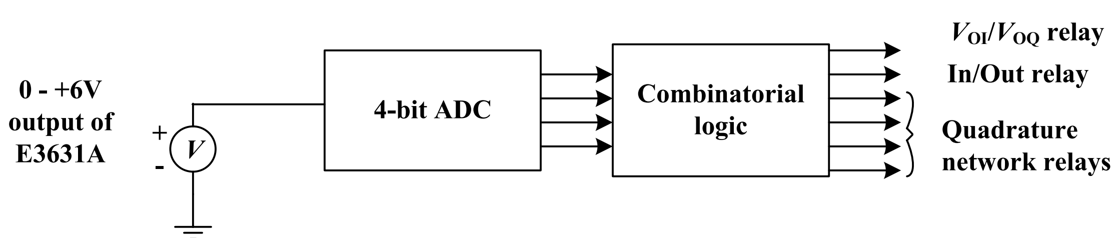

Fig. 3. Block diagram of the Project TUNA relay control unit.

Design of the relay control unit involved a compromise between flexibility and design complexity. The 4-bit ADC design allowed selection of 16 configurations: two possible states of the In/Out relay, two possible states of the V_{OI}/V_{OQ} relay, and one of four quadrature networks.

Curricular use and performance limitations of Project TUNA

Project TUNA was an immediate success when it was formally introduced into the curriculum in 2000. It was well received by the students who realized significant savings of time in laboratory procedures.[2] It is presently used for frequency response measurements in both EENG 3106 (Electronic Circuits I Laboratory) and EENG 4109 (Electronic Circuits II Laboratory). However, laboratory use demonstrated shortcomings of Project TUNA:

- Maximal measurement frequency is limited to 100kHz due to charge injection in the high-speed analog switches (ADG201HS) used in the phase-sensitive demodulator.
- The measurement time at each frequency is dictated by the *RC* time constant of the low-pass filters at the outputs of the phase-sensitive demodulator. The time constant chosen was 160ms, allowing a minimal measurement frequency of 10Hz but requiring approximately 1s for the dc voltage at the output of each filter to approach its asymptotic value after a change in measurement frequency or after switching the input of the phase-sensitive demodulator between the input and output of the network under test. Thus the measurement time at each frequency must be greater than 2s.
- The LabVIEW virtual instrument program of Project TUNA controls the amplitude of the input voltage to the network under test, but a practical lower limit of 1Vpp was found to be necessary to minimize jitter in the switching of the LM361 high-speed voltage comparators. This limits the maximal voltage gain of the network under test to approximately 29dB and also requires that the network under test remain in its linear operating range with an input of 1Vpp.
- The phase-sensitive demodulator's input is a unity-gain buffer amplifier with high input impedance (approximately 1MΩ), but the fixed gain of the buffer amplifier limits the minimal gain of the network under test to approximately –30 to –40dB, depending upon the maximum allowable input voltage of the network under test.
- Project TUNA required not only the custom hardware but a suite of GPIB-capable test equipment (signal generator, dc power supply, and digital multimeter) as well.

The impetus for Project TUNA II was to minimize these shortcomings. The goals of the Project TUNA II development were to extend the upper frequency range to 1MHz, increase the dynamic range of gain measurement to ±40dB, significantly reduce the analysis time, and reduce reliance on GPIB test equipment. Re-designed circuitry for the custom external hardware and installation of PCI-type plug-in data-acquisition cards in the laboratory computers made Project TUNA II possible.

Development of Project TUNA II

Development of Project TUNA II was undertaken as a senior design project for one student in the spring of 2001. Prototype hardware and a LabVIEW virtual instrument (created by modifying the virtual instrument of Project TUNA) were completed by the end of the semester. One copy of permanent hardware and improved software were completed in 2004.

Description of TUNA II hardware

The topology of Project TUNA II is shown in Fig. 4.

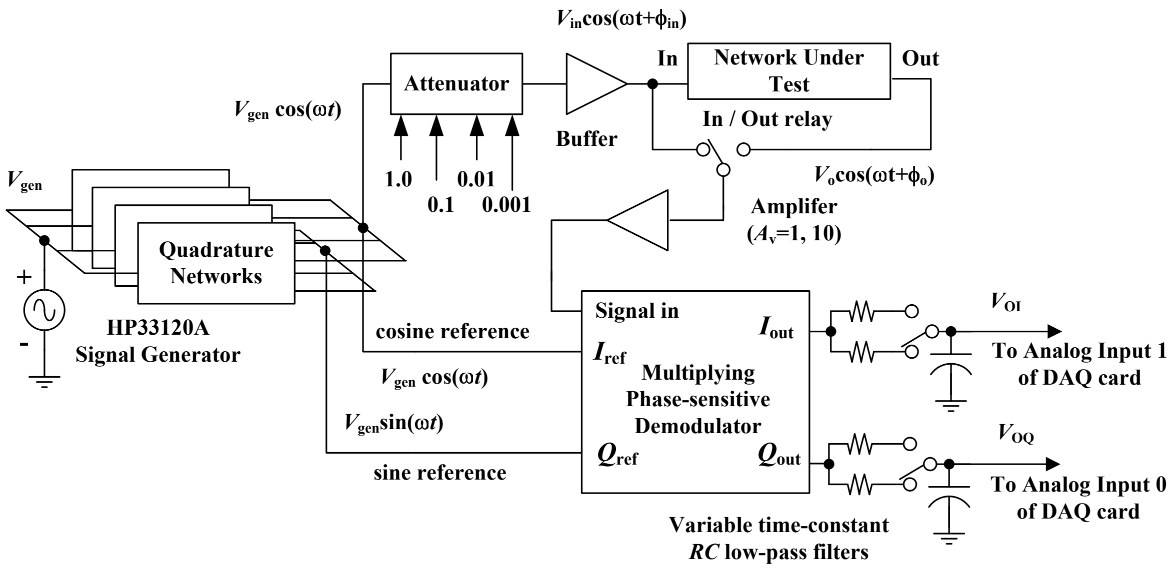

Fig. 4. Block diagram of the Project TUNA II hardware.

The salient differences between Project TUNA II and its predecessor are as follows:

- Project TUNA II utilizes a multiplying phase-sensitive demodulator in place of the switching type, extending the bandwidth and eliminating the high-speed voltage comparators.
- Project TUNA II includes an attenuator to adjust the voltage applied to the network under test over a range of 1000:1.
- Project TUNA II has selectable time-constant low-pass filters that shorten analysis times for measurement frequencies greater than ~200Hz.
- Project TUNA II includes an amplifier with selectable voltage gain (1 or 10) to extend the dynamic range of the instrument.
- Project TUNA II uses a PCI-type data-acquisition card to measure the dc output voltages V_{OI} and V_{OQ} simultaneously instead of sequentially.
- Project TUNA II uses digital outputs of the data-acquisition card to control the attenuator, In/Out Relay, amplifier gain, and low-pass filter time constant.
- Project TUNA II includes a fourth quadrature network (utilizing two poles per channel instead of four) covering the frequencies from 100kHz to 1MHz.
- Project TUNA II requires only one GPIB test instrument (HP 33120A arbitrary waveform generator).

TUNA II also requires a PC with a data-acquisition (DAQ) card and a GPIB card. The DAQ card must have at least two channels of analog input and an 8-bit digital output port. The present implementation of TUNA II utilizes a PCI-5070-E multifunction DAQ card (National Instruments, Austin, TX).

The multiplying phase-sensitive demodulator is realized with two AD734 wideband analog multipliers (Analog Devices, Norwood, MA). The use of analog multipliers as phase-sensitive demodulators with a sinusoidal reference is an example of homodyne detection.[3,4]

TUNA II computation of network voltage gain and phase

The dc output voltages of the multiplying phase-sensitive demodulator are:

$$V_{\mathrm{OIin}} = \frac{V_{\mathrm{in}} A_{\mathrm{in}} V_{\mathrm{gen}}}{20} \cos(\phi_{\mathrm{in}}) \tag{3a}$$

$$V_{\mathrm{OQin}} = -\frac{V_{\mathrm{in}} A_{\mathrm{in}} V_{\mathrm{gen}}}{20} \sin(\phi_{\mathrm{in}}) \tag{3b}$$

$$V_{\mathrm{OIo}} = \frac{V_{\mathrm{o}} A_{\mathrm{o}} V_{\mathrm{gen}}}{20} \cos(\phi_{\mathrm{o}}) \tag{3c}$$

$$V_{\mathrm{OQo}} = -\frac{V_{\mathrm{o}} A_{\mathrm{o}} V_{\mathrm{gen}}}{20} \sin(\phi_{\mathrm{o}}) \tag{3d}$$

where:

V_{OIin} and V_{OQin} are the dc voltages at the I_{out} and Q_{out} outputs of the demodulator with the demodulator connected to the input of the network under test;
V_{OIo} and V_{OQo} are the dc voltages at the I_{out} and Q_{out} outputs of the demodulator with the demodulator connected to the output of the network under test;
A_{in} is the voltage gain of the amplifier when reading the input of the network under test;
A_{o} is the voltage gain of the amplifier when reading the output of the network under test;
V_{in} is the amplitude of the voltage at the input of the network under test;
V_{o} is the amplitude of the voltage at the output of the network under test;
V_{gen} is the amplitude of the output voltage of the generator
φ_{in} is the phase of the voltage at the input of the network under test;
φ_{o} is the phase of the voltage at the output of the network under test.

From these readings, network voltage gain A_{v} and phase φ are computed as follows:

$$A_{\mathrm{V}} = 20 \log_{10} \frac{A_{\mathrm{in}}}{A_{\mathrm{o}}} \sqrt{\frac{V_{\mathrm{OIo}}^2 + V_{\mathrm{OQo}}^2}{V_{\mathrm{OIin}}^2 + V_{\mathrm{OQin}}^2}} \tag{4a}$$

$$\phi_{\mathrm{in}} = \tan^{-1}\left(\frac{-V_{\mathrm{OQin}}}{V_{\mathrm{OIin}}}\right) \tag{4b}$$

$$\phi_{\mathrm{o}} = \tan^{-1}\left(\frac{-V_{\mathrm{OQo}}}{V_{\mathrm{OIo}}}\right) \tag{4c}$$

$$\phi = \phi_{\mathrm{o}} - \phi_{\mathrm{in}} \tag{4d}$$

Description of TUNA II software

The virtual instrument (VI) program of TUNA II runs in the LabVIEW 7.0 environment. The front panel of the TUNA II VI is shown in Fig. 5.

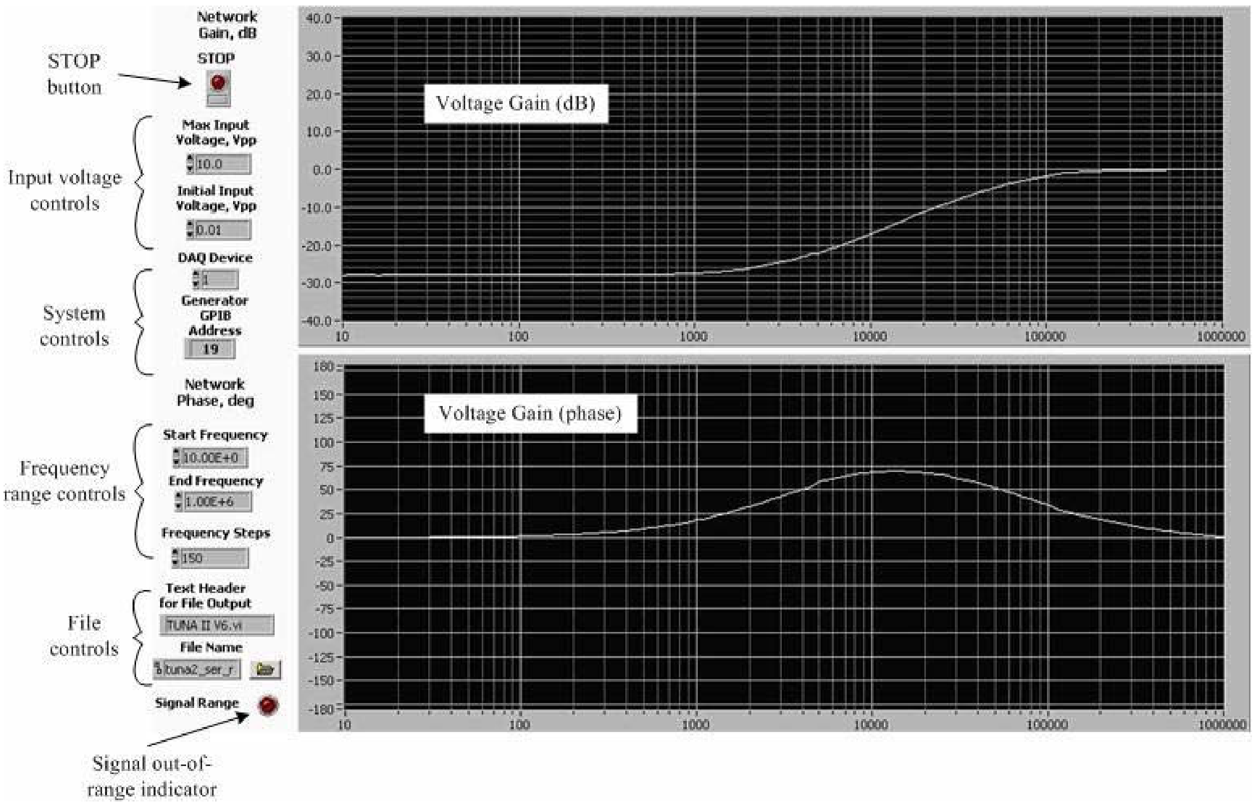

Fig. 5. Front panel of the TUNA II virtual instrument showing the magnitude and phase response of an *RL* network from 10Hz to 1MHz. The magnitude response reaches an asymptotic limit as frequency decreases rather than continuing to decline because of the parasitic resistance of the inductor.

The user controls are as follows:

- STOP button: used to terminate an analysis prematurely.
- Input voltage controls: specify the initial input voltage and maximal input voltage to be applied to the network under test.
- System controls: specify the device number of the DAQ card and the GPIB address of the function generator.
- Frequency range controls: specify the start and end frequencies of the analysis and the total number of analysis points.
- File controls: specify the path and name of the output file for results.
- Signal out-of-range indicator: illuminates during analysis if the input signal becomes too small or too large for reliable reading.

The output of TUNA II is a Bode plot with separate plots for magnitude (–40dB to +40dB) and phase (–180° to +180°) of the voltage gain of the network under test over a range of 10Hz to 1MHz.

The virtual instrument includes automatic control of both the attenuator settings and the variable-gain amplifier.

Examples of TUNA II measurements

Figure 6 is the schematic of a bandpass filter that was analyzed with Project TUNA II. The filter's design performance is for a center frequency of 1kHz with a voltage gain of 20dB and a *Q* of 10.

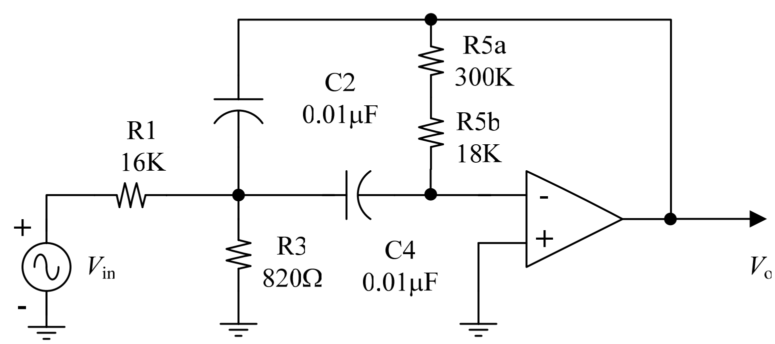

Fig. 6. Active bandpass filter. The operational amplifier is ¼ TL084.

Figure 7 shows the measured voltage gain (magnitude and phase) of this filter over a frequency range of 100Hz to 10kHz as graphed with Excel from data exported from the TUNA II virtual instrument program. The measured response corresponds well to expectations, although the magnitude of the gain does not quite reach the expected maximum. This is not surprising, however, given the limited number of frequencies (80 steps) and the high *Q* of the filter. The greatest discrepancy between expectations and results is the apparent discontinuity in phase measurement beyond 4.8kHz. This is a consequence of the switching from one quadrature network to the next at 4750Hz. There is a small error in phase relationship of the two outputs of the third quadrature network, and the phase reading of TUNA II is the most sensitive to phase error of the quadrature network when the network phase is a multiple of ±90°. (Under these circumstances, the error in the network phase reading is approximately equal to the phase error of the quadrature network). Phase error in the quadrature network also produces an error in the reading of the network voltage gain. Computations show that the error in voltage gain due to phase error in the quadrature network is maximal when the network phase is a multiple of ±45° but is small even under these circumstances (<0.5dB with a quadrature network phase error of ±5°).

The measurement shown in Fig. 7 required 1mn 10s with TUNA II. The same filter was analyzed with Project TUNA with similar results, but it required 6mn 24s for the same analysis.

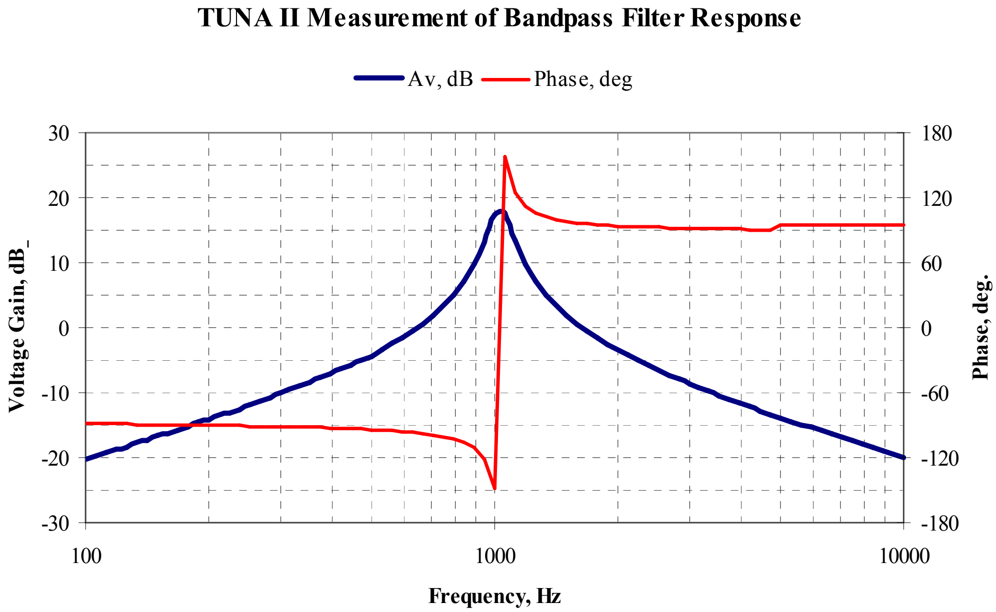

Fig. 7. Frequency response of the bandpass filter of Fig. 6 measured with the Project TUNA II instrument.

Figure 8 is the schematic of a series *RLC* circuit that includes a parasitic resistance in the inductor. The expected series-resonant frequency is 229kHz, and voltage gain of the network should be approximately 10dB.

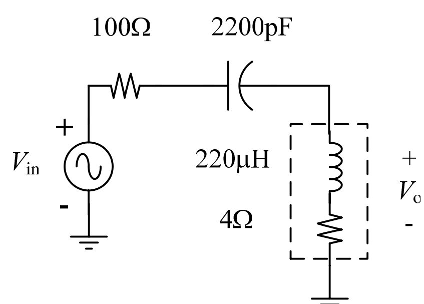

Fig. 8. Series *RLC* network analyzed by TUNA II. The 4Ω resistance represents the parasitic dc resistance of the inductor.

Figure 9 is the frequency response of the circuit of Fig. 8 as measured by TUNA II. The analysis required 46s to complete. The response is in agreement with expectations. Comparison of the data from TUNA II with PSpice simulation shows a magnitude error of 1dB or less and a phase error of 4° or less over the range of frequencies from 30kHz to 300kHz.

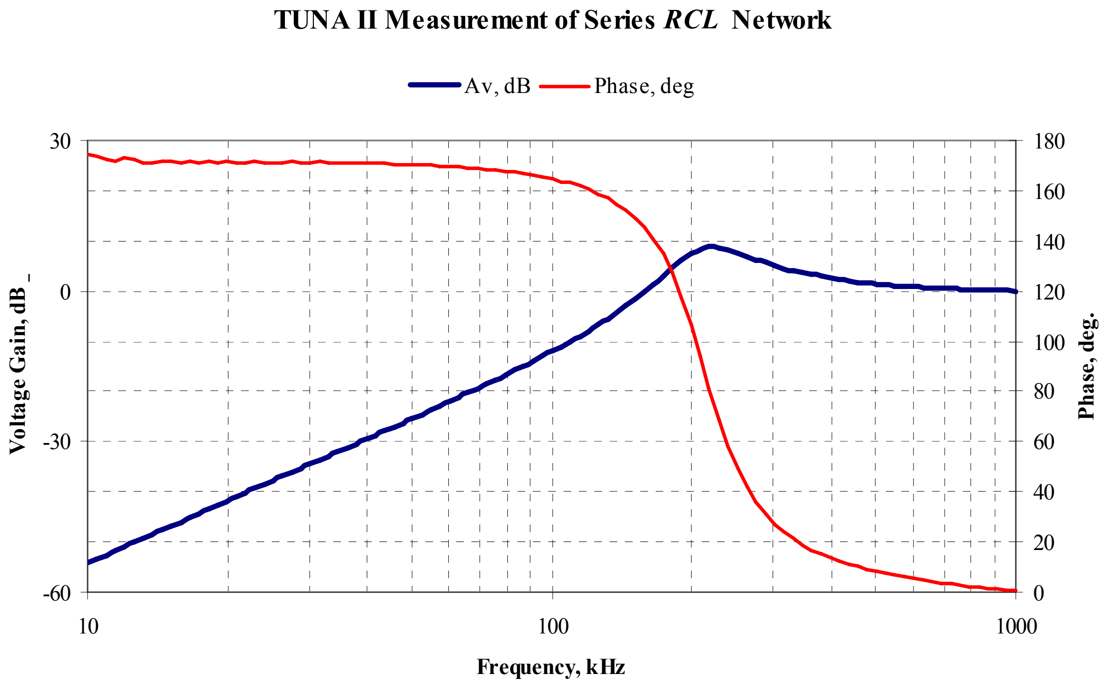

Fig. 9. Frequency response of the circuit of Fig. 8 measured by TUNA II. The phase does not asymptotically approach 180° at lower frequencies because of the parasitic resistance of the inductor.

Instructional use of Project TUNA II

Project TUNA II has been used as a laboratory instrument at UT-Tyler in both EENG 3106 and EENG 4109 (Electronic Circuits Analysis I and II Laboratories, respectively). It is particularly useful in EENG 4109 in an extensive laboratory exercise on active filters where its time savings relative to its predecessor are significant. TUNA II was also used extensively in the design verification of an electrically-tuned continuous-time elliptical anti-aliasing filter designed as a senior capstone design project in 2005.

Project TUNA and Project TUNA II have been used as teaching tools to explain the principles of phase-sensitive demodulation in both EENG 4309 (Electronic Circuits Analysis II) and EENG 4302 (Measurement and Instrumentation Systems). Resources created in conjunction with TUNA II include an introductory tutorial on phase-sensitive demodulation and an Excel spreadsheet to automate the design process for quadrature networks.

Schematic diagrams, parts lists, circuit-board layouts (in AutoCAD form) and the LabVIEW virtual instrument code are available from http://ee.uttyler.edu/David_Beams/project_page.htm.

Conclusion

Project TUNA II has been and continues to be a valuable component in the teaching mission of the Department of Electrical Engineering. It was a successful senior project that was particularly valuable in exposing its developer to aspects of high-speed analog design and development of LabVIEW virtual instruments. TUNA II allows students to make frequency-response plots in a relatively-short period of time in its role as a laboratory instrument; and its open documentation and supporting documentation make TUNA II a useful platform for teaching concepts in phase-sensitive demodulation and high-speed analog design.

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Bibliography

[1] Keely, T. A. Design of constant phase difference networks. *RF Design* 12 (4), pp. 32, 37, 38, 40, 42 (April, 1989).
[2] D. M. Beams, *Project TUNA: the development of a LabVIEW virtual instrument as a class project in a junior-level electronics course.* Proceedings of the 2000 Annual Conference of the American Society for Engineering Education, St. Louis, MO, June 18–21, 2000
[3] Stremler, F. G., *Communication systems, 3rd Ed.* Reading, MA: Addison-Wesley, 1990, p. 223.
[4] Webster, J.G., and Pallàs-Areny, R., *Sensors and signal conditioning, 2nd Ed.* New York: John Wiley & Sons, 2001, p. 306.