

## Developing Computer-Based Laboratory Instruments in a New Undergraduate Electrical Engineering Program

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**ABSTRACT:** The Department of Electrical Engineering of the University of Texas at Tyler has developed several computer-based laboratory instruments (CLIs) consisting of LabVIEW virtual-instrument programs coupled with custom external hardware and has integrated their use into the undergraduate curriculum. Semiconductor curve tracers for diodes, JFETs, MOSFETs, and bipolar transistors have been incorporated into EENG 3406 (Electronic Circuit Analysis I). Project TUNA (Texas Universal Network Analyzer), a CLI which characterizes the frequency response (magnitude and phase) of linear networks over a frequency range of 10 Hz to 100 kHz was designed as a class project in 1999 in EENG 4409 (Electronic Circuit Analysis II). A grant was received from the National Science Foundation in February, 2000, to support the development and curricular integration of additional CLIs, two of which are described in this paper. The first measures electrical characteristics of operational amplifiers (input-offset voltage, input-bias currents, dc open loop gain, and ac open-loop gain at 1 kHz and 10 kHz). It has been designed, constructed in prototype form, and integrated into EENG 4409. The second instrument under development is a general-purpose workbench for teaching about instrumentation systems. This paper presents developments to date, describes curricular use of the instruments, and gives an overview of the expected path of the second year of this project.

Prior developments in instructional computer-based laboratory instrumentation

The use of virtual instrumentation in the undergraduate curriculum is well-documented; the National Science Foundation has funded a number of efforts in this regard.<sup>1-5</sup> Development of instructional computer-based laboratory instruments (CLIs) has taken place at the University of Texas at Tyler since its College of Engineering opened in 1997. A series of CLIs have been developed for tracing the I-V curves of semiconductor devices (p-n junction diodes, NPN and PNP small-signal bipolar transistors, and n-channel JFETs and MOSFETs). These have been previously described.<sup>6</sup> Project TUNA, a CLI which measures sinusoidal steady-state response of linear networks, was designed, constructed in prototype form, and tested as a class project in the spring semester of 1999 in EENG 4409 (Electronic Circuit Analysis II). A description of Project TUNA has been published.<sup>7</sup> On-line documentation of Project TUNA is available at [http://www.eng.uttyl.edu/usr/dbeams/home/project\\_page.htm](http://www.eng.uttyl.edu/usr/dbeams/home/project_page.htm). Each of these CLIs has been incorporated into the curriculum. The curve tracers are used as primary teaching tools in EENG 3406 (Electronic Circuit Analysis I) and. Project TUNA is now incorporated into the laboratory of EENG 4409. They also provide instructional opportunities to explain their principles of operation.

Project TUNA and the curve-tracer CLIs utilize GPIB-based test equipment and some external hardware. Permanent custom hardware has been constructed for the bipolar-transistor curve tracers and for Project TUNA. The custom hardware required for the diode and FET curve tracers is very simple and did not justify permanent construction. The use of GPIB-based test equipment does have drawbacks: the test equipment is much more expensive than a computer-based data-acquisition card, and the GPIB instruments lack addressable digital ports. Further developments in CLIs at the University of Texas at Tyler will avoid GPIB-based designs whenever possible.

## Project TUGBOAT

Operational amplifiers are in widespread use in electronic systems; a working understanding of op amps is important to the circuit designer whose practice involves analog circuits of any type. Students are introduced to op amps using a model with idealized characteristics:<sup>8</sup>

- Infinite input impedance
- Infinite differential-mode voltage gain  $A_v$
- Zero output impedance
- Infinite bandwidth
- Zero common-mode gain

This most-simple model of the operational amplifier as a voltage-controlled voltage source is depicted in Fig. 1. The output voltage  $V_o$  is the product of the differential-mode input voltage  $V_{dm} = (V_+ - V_-)$  and differential-mode voltage gain  $A_v$ .

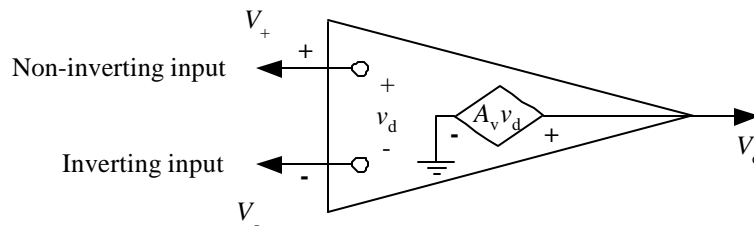


Fig. 1. Simple electrical model of an ideal operational amplifier.

These simplifications allow students to learn the essential principles of design and analysis of op amp circuits. Successful design of high-performance analog circuits, however, requires an understanding of the limitations of the ideal model and the effects of non-ideal characteristics of operational amplifiers on circuit performance. Non-zero input-offset voltages cause dc output-voltage errors; input-bias currents cause dc errors in amplifier circuits and cause the output voltage of integrators to drift with time. Closed-loop gain errors result from limited open-loop differential-mode voltage gain. Limited bandwidth causes high-frequency behavior of circuits to differ significantly from that predicted by the idealized model. A more-comprehensive model of an operational amplifier is shown in Fig. 2. This is by no means an exhaustive catalog of non-idealities in real operational amplifiers. Not considered in the list above are limited slew rate,

nonzero output impedance, response to common-mode input voltages, limited output voltage range, limited common-mode input voltage range, and limited output current capability.

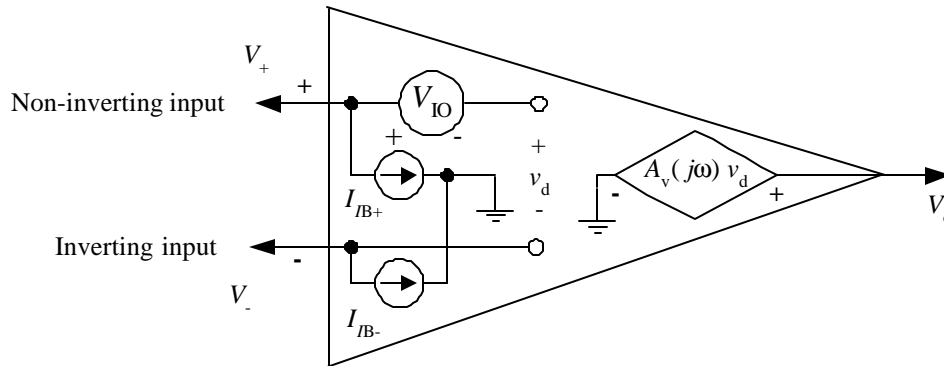


Fig. 2. A more-comprehensive model of the operational amplifier including the effects of input-offset voltage ( $V_{IO}$ ), input-bias currents ( $I_{IB+}$  and  $I_{IB-}$ ), and limited, frequency-dependent open-loop differential voltage gain ( $A_v(j\omega)$ ).

A laboratory exercise in non-ideal characteristics of operational amplifiers has been incorporated in EENG 4409 since it was first offered at the University of Texas at Tyler in 1998. Students constructed various circuits and used measurements made from these circuits to compute input-offset voltage, input-bias current, and open-loop gain vs. frequency. Op amp parameters determined in this exercise were compared to data-sheet values. However, the actual values of these parameters remained unknown since no independent means of measurement was available.

Project TUGBOAT (Texas UnderGraduate Basic Op Amp Tester) was conceived as a CLI to help in teaching non-ideal characteristics of operational amplifiers by providing a means of independent measurement. Table 1 below summarizes the measurement parameters and ranges of the Project TUGBOAT instrument.

Parameter	Range(s)
Input-offset voltage	0- $\pm 2$ mV, 0- $\pm 20$ mV
Input-bias currents	0- $\pm 0.35$ $\mu$ A, 0- $\pm 3.5$ $\mu$ A
DC open-loop gain	<50000, 50000-500000, >500000
AC open-loop gain @ 1 kHz	0-30000
AC open-loop gain @ 10 kHz	0-30000

Table 1. Measurement parameters and available measurement ranges of the Project TUGBOAT instrument. Ranges are manually selected for dc parameters; the instrument does not at present support autoscaling.

The ranges chosen permit the instrument to characterize a number of op amp types commonly encountered in undergraduate electronics courses such as the LM741, LM324, and the TL084. The instrument is not however restricted to these types.

The instrument in block diagram form appears in Fig. 3. A multifunction I/O card (PCI-1200) acquires data and configures the external hardware under control of a LabVIEW virtual-instrument program. The external hardware includes a Wein-bridge oscillator, a full-wave precision rectifier, and two-pole low-pass filter for measurement of ac open-loop gain. Thus only dc voltages need be measured in this instrument. The only test equipment required in addition to the Project TUGBOAT hardware is a dc power supply of  $\pm 15V$ . The measurement techniques used in the instrument were described by an application note from Analog Devices.<sup>9</sup>

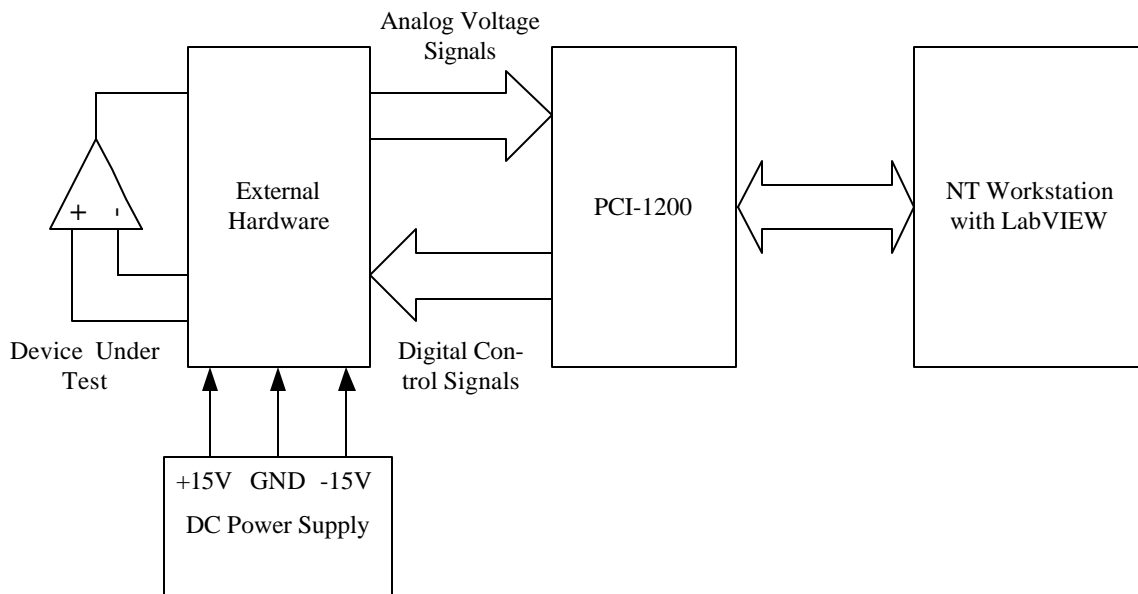


Fig. 3. Block diagram of the Project TUGBOAT instrument.

Figure 4 below depicts the dc measurement circuits of the instrument. The heart of the dc measurement circuits is an integrator utilizing precision operational amplifier  $U_2$ .  $V_o$  is the output voltage of the device under test scaled by a resistive voltage divider consisting of  $R_9$  and  $R_{10}$ .  $E_o$  is the output voltage of the integrator. Both are read by analog inputs of the PCI-1200.  $DAC_0$  and  $DAC_1$  are the output voltages of the digital-to-analog converters of the PCI-1200.

Input-offset voltage ( $V_{IO}$ ) of the device under test is read first. Both  $DAC_0$  and  $DAC_1$  are set to 0V and the switches shunting  $R_2$  and  $R_4$  are closed; power is applied to the device under test and the system is allowed to settle.  $E_o$  is fed back to the device under test through the feedback network consisting of  $R_1$ ,  $R_3$ ,  $R_6$ , and the resistive voltage divider. The steady-state value of  $E_o$  is that required to cancel  $V_{IO}$ .

Input-bias currents are determined next.  $DAC_0$  is set to the value that nulls  $V_{IO}$  and the integrator output  $E_o$  is read. The switch shunting  $R_2$  is opened and the integrator output is again read. The input-bias current of the noninverting input ( $I_{IB+}$ ) produces a voltage in  $R_2$  which appears as a change in input-offset voltage.  $I_{IB+}$  is computed as the apparent change in  $V_{IO}$  divided by  $R_2$ . The switch shunting  $R_2$  is closed. The process is repeated with the switch shunting  $R_4$  to compute the input-bias current of the inverting input ( $I_{IB-}$ ).

Open-loop voltage gain ( $A_v$ ) is computed last.  $DAC_1$  is set to +4.00V; integrator output  $E_o$  moves to the value required to force  $V_{o1}$  to cancel  $DAC_1$  at the summing junction of the integrator.  $E_o$  and  $V_o$  are read;  $DAC_1$  is then set to -4.00V and  $E_o$  and  $V_o$  are again read. The change in  $V_o$  is divided by the change in  $E_o$  and the attenuation of the feedback network gives  $A_v$ .

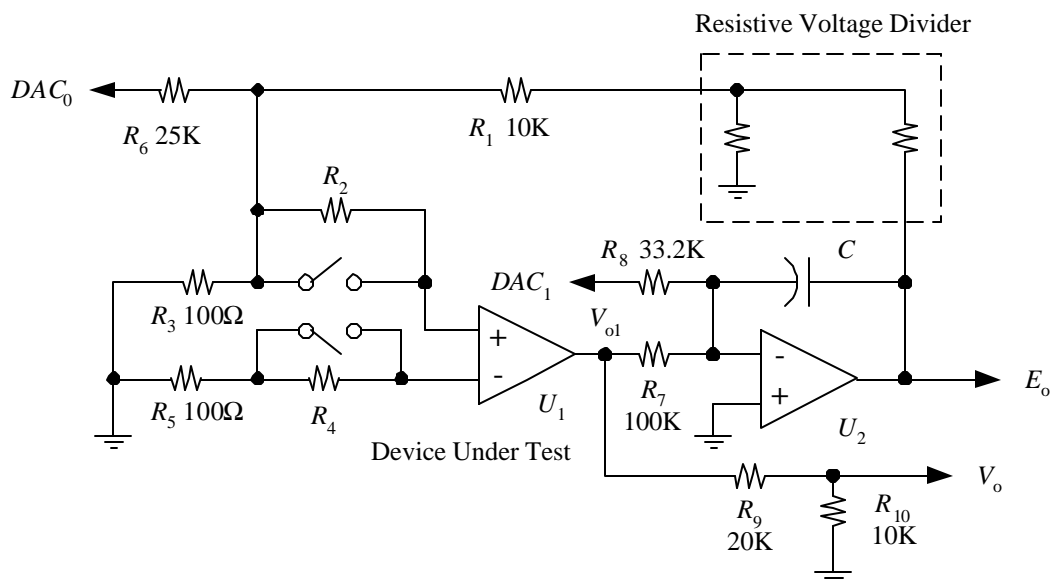


Fig. 4. Dc measurement circuits of the Project TUGBOAT instrument. The voltage divider provides attenuations of 1, 0.1, and 0.01 while maintaining a constant output resistance of 15K $\Omega$ .

Figure 5 shows the ac measurement circuits. Both the output voltage of the device under test and the output voltage of the generator are measured, permitting the use of a simple oscillator without calibration of its output voltage amplitude. The attenuation  $m$  of the generator output voltage may take on values of 1, 0.1, 0.01, and 0.001. The gain of the integrator is sufficiently low at the measurement frequencies of 1 kHz and 10 kHz that the device under test is operating open-loop.

A complete description of the Project TUGBOAT instrument may be obtained on-line at [http://www.eng.uttyl.edu/usr/dbeams/home/tugboat/tugboat\\_description.zip](http://www.eng.uttyl.edu/usr/dbeams/home/tugboat/tugboat_description.zip). Schematics are available from [http://www.eng.uttyl.edu/usr/dbeams/home/tugboat/tugboat\\_unit.pdf](http://www.eng.uttyl.edu/usr/dbeams/home/tugboat/tugboat_unit.pdf).

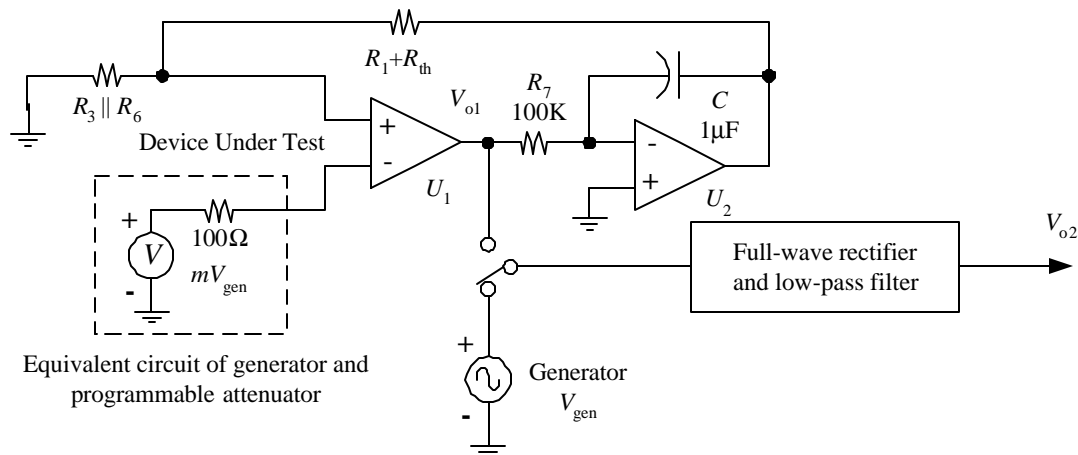


Fig. 5. Ac measurement circuits of the Project TUGBOAT instrument. Output voltage  $V_{o2}$  of the low-pass filter is read by one of the analog channels of the PCI-1200 card.

A prototype instrument was developed and tested as a class project in EENG 4409 in the spring semester of 2000. It was not possible to develop the LabVIEW virtual-instrument program during the course of the semester, however, as funds to purchase the PCI-1200 multi-function I/O cards did not become available until April, 2000. Students did, however, construct the circuitry of the external hardware. Control of the hardware was manual, and a dc voltmeter was used to make measurements. Students were asked to compare their results to data-sheet values, and measured values were found to be within the ranges specified by the manufacturers. In addition, students used measured ac open-loop gain at 1 kHz and 10 kHz to compute estimates of the gain-bandwidth product (GBW) of their operational amplifiers; the computed GBW was then used to predict the closed-loop cutoff frequency of a high-gain ac amplifier. Students measured the cutoff frequencies of their amplifier circuits, and good agreement between predicted and measured values.

The prototype instrument has since been integrated with a LabVIEW virtual-instrument program to form a complete CLI. Fig. 6 below shows the front panel of the LabVIEW virtual instrument.

Curricular materials have been prepared for use in EENG 4409. These include a laboratory exercise in which students will compare values from the Project TUGBOAT tester with values obtained from measurements taken from circuits using those operational amplifiers. Examples of results obtained with LM741, LM324, and TL084 operational amplifiers are shown in Figs. 7, 8, and 9. The data presented in these figures is the work of one user; results obtained by others were similar. The abscissa data in each graph are values computed from measurements of circuits; the ordinate data are values determined by the Project TUGBOAT tester.

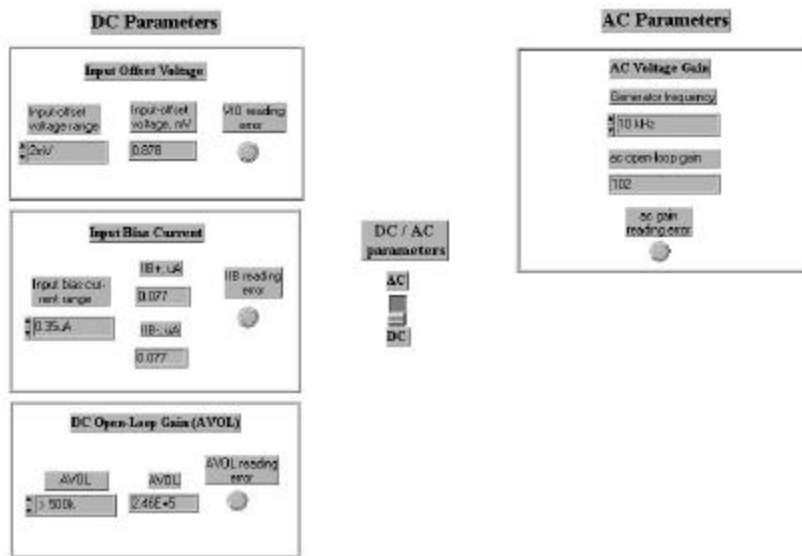


Fig. 6. Front-panel controls of the Project TUGBOAT tester. The indicated values are from measurements taken from an LM741.

Figure 7 shows the comparison of input-offset voltage as determined by the Project TUGBOAT instrument with the input-offset voltage computed from the output-offset voltage of a high-gain dc-coupled noninverting amplifier with nominal gain of 561.

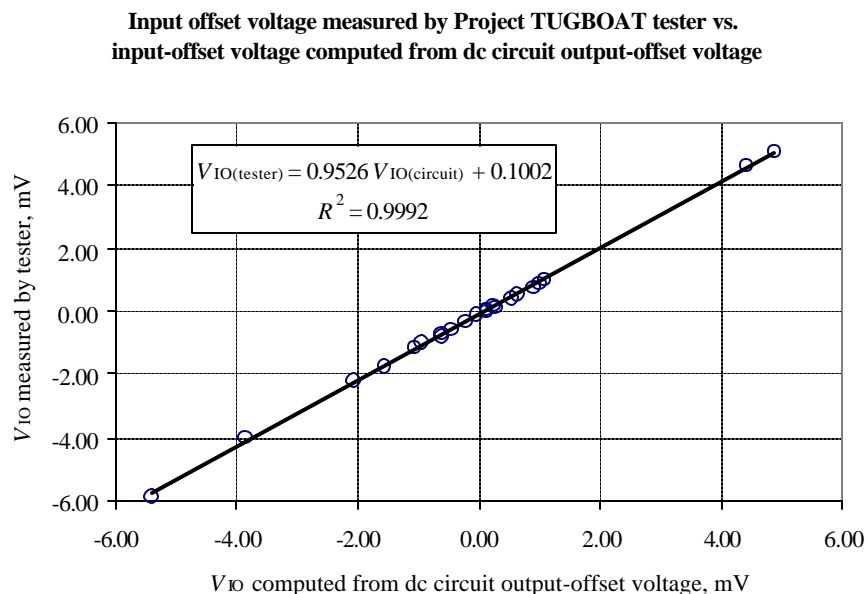


Fig. 7. Comparison of input-offset voltages measured by Project TUGBOAT tester with values computed from the output-offset voltage of a high-gain dc-coupled amplifier.

Figure 8 compares the input-bias current of the inverting input measured by the tester with values computed from the drift with respect to time of the output voltage of an integrator. The agreement is excellent.

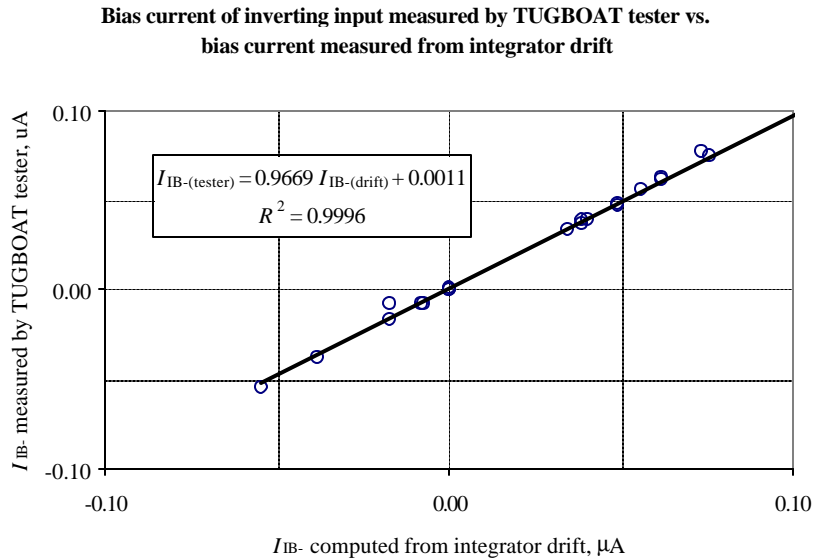


Fig. 8. Comparison of input-bias currents measured by the Project TUGBOAT tester with values computed from drift of the output voltage of an integrator with respect to time.

Data points in Fig. 8 with negative values are from LM324 devices with PNP inputs; positive data points are from LM741 devices with NPN inputs. TL084 devices have JFET inputs and have input-bias currents of 1nA or less and are responsible for the cluster of data points near the origin in Fig. 8.

Figure 9 shows predicted corner frequencies vs. measured corner frequencies for a high-gain ac-coupled amplifier. Predicted corner frequencies were determined from the design closed-loop gain of the amplifier and the ac open-loop gain measured by the TUGBOAT instrument. There appears to be a systematic underprediction of the closed-loop corner frequency.

Table 2 shows measured dc open-loop voltage gains and gain-bandwidth products for all devices in this study, which included a CA224 device and two LM6361 high-speed amplifiers. The one surprising result is the high open-loop gain manifested by the LM741s, LM324s, and the CA224. Equally surprising was the variation in open-loop gain between LM741s from different manufacturers; the mean dc open-loop gain of devices from National Semiconductor was  $2.89 \times 10^6$  while that of devices from Harris Semiconductor was  $2.48 \times 10^5$ . No other manufacturer-specific trends were observed.



Computed vs. measured  $f_{-3dB}$  of ac circuit

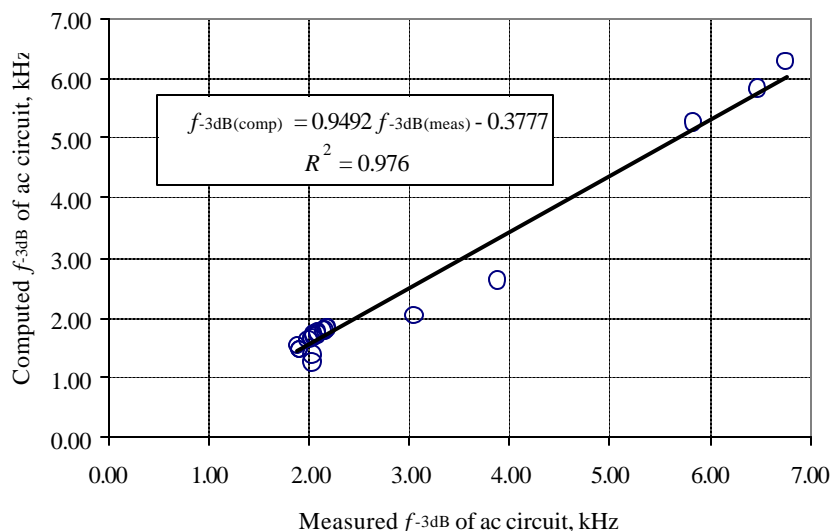


Fig. 9. Comparison of measured corner frequency of a high-gain ac-coupled amplifier with the expected corner frequency based upon measurement of gain-bandwidth product with the Project TUGBOAT tester.

Device type	dc open-loop gain	GBW, MHz
TL084 ( $n=3$ )	$9.413 \times 10^4 \pm 1.208 \times 10^4$	$3.227 \pm 0.288$
LM741 ( $n=11$ )	$1.926 \times 10^6 \pm 1.371 \times 10^6$	$0.960 \pm 0.049$
LM324 ( $n=6$ )	$2.138 \times 10^6 \pm 6.120 \times 10^5$	$0.913 \pm 0.316$
CA224 ( $n=1$ )	$4.431 \times 10^6$	1.130
LM6361 ( $n=2$ )	$4408 \pm 719$	$53.5 \pm 0.2$

Table 2. Summary of dc open-loop voltage gains and gain-bandwidth products for all operational amplifiers in the preliminary study of the Project TUGBOAT tester. Figures represent mean values  $\pm$  standard deviations except for the CA224 device.

The prototype Project TUGBOAT tester was used for instructional purposes for the first time in EENG 4409 in the spring semester of 2001. Fabrication of two permanent instruments with printed-circuit board construction is under way.

### Instrumentation System CLI

The second CLI to be developed in this project will support a course in instrumentation systems at the University of Texas at Tyler. Design and test of the various components of this CLI have

been carried out as a class project in EENG 4409 in the spring of 2001. Figure 10 shows the configuration of the hardware this CLI.

The quadrature oscillator provides sine and cosine signals at 1 kHz or 10 kHz with 4-bit amplitude control; frequency and amplitude are selected by the user by means of a LabVIEW virtual-instrument program.

An instrumentation amplifier with gains of 1, 10, and 100 selectable by LabVIEW has been constructed. A two-channel electronically-controlled switch has been constructed from which chopper-stabilized amplifiers and phase-sensitive demodulators (lock-in amplifiers) may be constructed. Electronic cold-junction compensation will be provided for developing thermocouple amplifiers. The LabVIEW virtual instrument program is currently under development; the finished program will contain controls for the various circuits and a continuous strip-chart display of analog inputs.

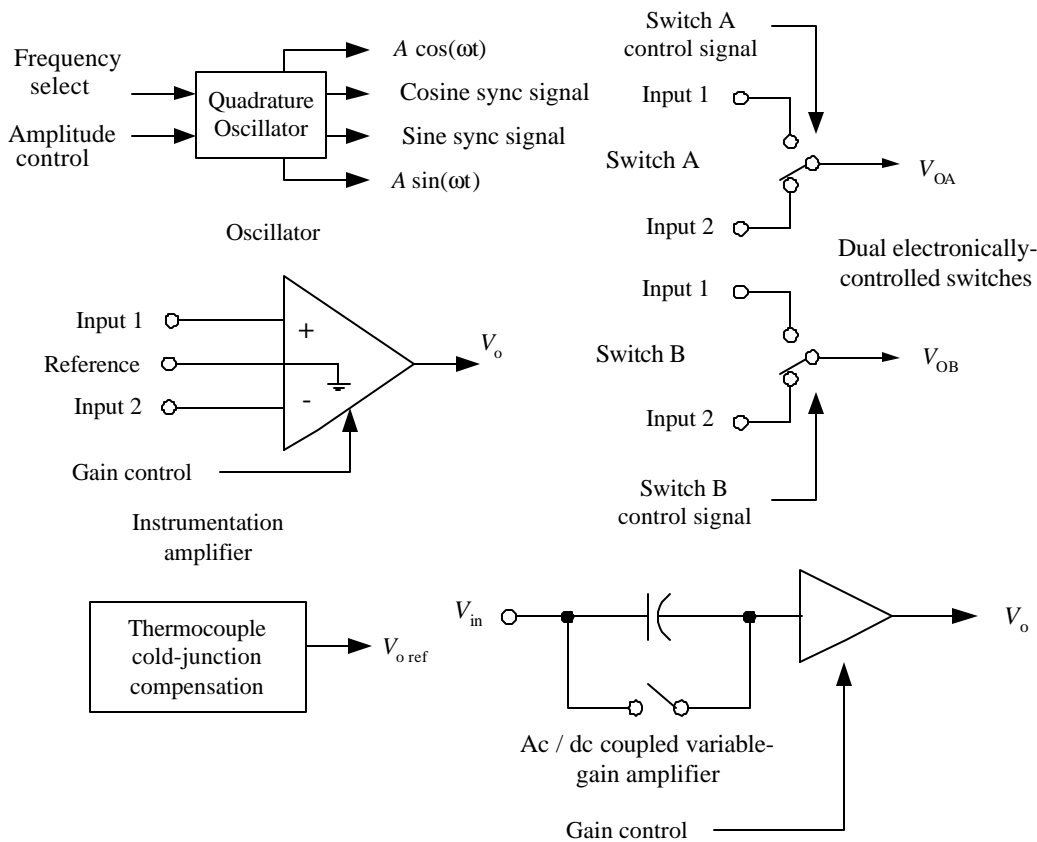


Fig. 10. Components of the custom external hardware of the instrumentation interface CLI developed as a class project in EENG 4409 (Electronics II) in spring, 2001.

A typical application for the instrumentation-system CLI is shown in Fig. 11. The cosine output of the quadrature oscillator is used to drive the primary of an LVDT; the variable-gain ac/dc-coupled amplifier provides gain and one of the two independent electronically-commutated switches is used with an external low-pass filter to make a switching-type phase-sensitive detector (lock-in amplifier).

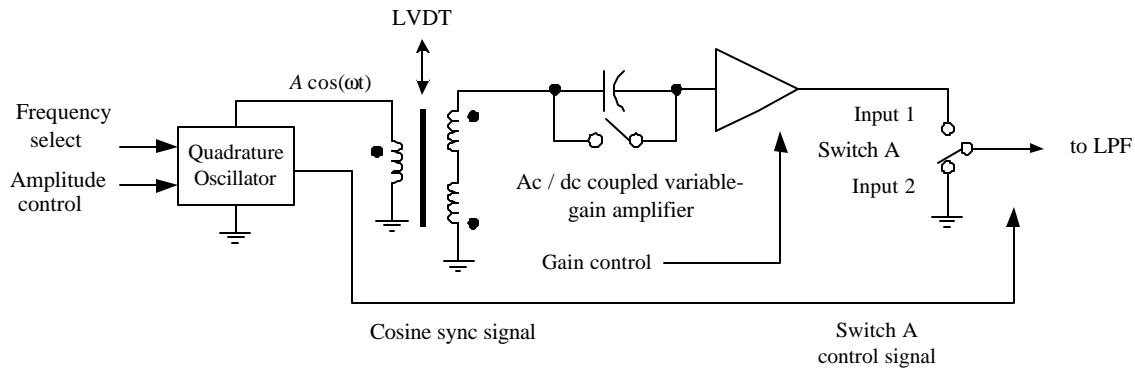


Fig. 11. Typical possible application using components of the instrumentation-system CLI.  
Future Developments

Two further CLIs are planned for the second year of this two-year project. One is an instrument to support a laboratory on rotating machines (measurement of voltages, currents, RPM, and torque in real time); the second is an instrument for measuring impedances similar to commercially-available LCR bridges. Students in EENG 4409 will be brought into the design and development of both instruments.

A booklet describing the available CLIs with detailed instructions for duplicating them is planned for summer, 2002.

TUNA II has been undertaken as a capstone design project for the spring semester of 2001 by senior EE student Zinnour Soultanov. TUNA II is planned to extend the maximal usable frequency of the instrument from 100 kHz to 1 MHz and to speed data-taking by having selectable corner frequencies of the I-Q demodulator's low-pass filters (allowing a corner frequency appropriate to the frequency of measurement at any given time). It is also planned to utilize the PCI-1200 data-acquisition card to replace GPIB-based test equipment used with Project TUNA. TUNA II will require only one GPIB-based test instrument (the HP33120A arbitrary waveform generator) compared with three instruments in Project TUNA. Hardware design is largely complete at this writing.

## Acknowledgement

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