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Work in Progress: Sensory feedback in electric circuit laboratories

Mr. Brian E. Faulkner, Milwaukee School of Engineering

Brian Faulkner's interests include teaching of modeling, engineering mathematics, textbook design, and engineering epistemology.

Dr. Daniel Maguire, Valparaiso University

Daniel Maguire is an Assistant Professor of Electrical and Computer Engineering at Valparaiso University. His teaching and research interests include adaptive control systems, active noise and vibration control, signal processing, and instructional methods for signals and systems.

Jennifer Marley, Purdue University at West Lafayette (COE)

Jennifer Marley is an assistant professor of electrical and computer engineering at Valparaiso University. She received the B.S. degree in electrical engineering from North Carolina State University and M.S. and Ph.D. degrees in electrical engineering: sy

WORK IN PROGRESS: Sensory feedback in laboratories for introductory circuit theory courses

Brian Faulkner
Electrical and Computer Engineering Department
Milwaukee School of Engineering

Jennifer F Marley, Daniel J Maguire
Electrical and Computer Engineering Department
Valparaiso University

Abstract

WORK IN PROGRESS: Most engineering students take a course in electric circuits. In a typical circuit laboratory, the focus is on discrete passive components: resistors, inductors, and capacitors. These components do not convert any energy into a form that can be detected by the human senses. The function of the circuit can only be probed with the instrumentation. In this study, we explore the effect of incorporating a transducer (a loudspeaker) as a circuit component. The control group of students construct a high-pass filter with a discrete resistor and capacitor. The experiment group uses a loudspeaker instead of a resistor. Both groups perform a frequency sweep to see the transfer function of the filter. The frequency of the signal manifests itself as the pitch of the sound from the speaker, and the magnitude manifests as the sound volume. Through a brief survey instrument, we investigate how the additional information present in the sound produced by the loudspeaker affects student understanding of high pass and low pass systems and ability to diagnose errors in hardware circuit implementation. Many students reported using their perception of the frequency and volume of the tonal output in their assessment of the circuit purpose (lowpass/highpass). Overall, the students used the output of the speaker to troubleshoot and validate their circuit. Human factors issues related to audible perception were also observed. Qualitative data indicates students use the sensory feedback to interpret the quantitative data and identify errors in their hardware setup.

Introduction and Background

The study of electric circuits is a required course in many engineering majors. Circuits is the primary introductory course sequence in electrical and computer engineering programs. It is also the gateway to more advanced study in instrumentation and controls in biomedical or mechanical engineering. Circuits is a high-enrollment course that several majors must pass to complete degrees in engineering.

Laboratory study is an important component of many engineering classes. Laboratories offer many important contributions to engineering classes, as summarized in Fiesel, 2005. This work directly addresses one objective listed by Fiesel: "*Objective #13 Sensory Awareness: Use the human senses to gather information and to make sound engineering judgements in formulating* *conclusions about real-world problems"*. From Fiesel, 2005. In many circuit theory laboratories, the only components used are discrete passive resistors, inductors, and capacitors, which offer little output that can be observed with the senses. Conversely, circuits with transducers (light sensors, motors, speakers, etc) produce output that interacts with the human senses.

While audible signals are often the focus of frequency response measurements (room acoustics, etc) and frequency response measurement devices exist having audio outputs, there has been no consensus on including audible/tactile feedback as a best practice in the frequency response instruction.

An additional crucial component of Objective #13 *Sensory Awareness* is the link to the idea of troubleshooting. Dounas-Frazier & Lewandowski summarize the value and purpose of developing troubleshooting skills (Dounas-Frazier & Lewandowski, 2017) . Previous studies have explored the effect of worked examples in circuit troubleshooting (van Gog *et al*, 2006), reasoning with multiple faults (de Kleer and Williams, 1986), metacognition in amplifier troubleshooting (Van de Bogart & Dounas-Frazier, 2015), and the substitution of virtual laboratories for physical laboratories (Finkelstein *et al*, 2005).

This study investigates the effect on student conceptual understanding and troubleshooting in circuits laboratories when a component with sensory output is added: a loudspeaker. Unlike a discrete resistor, the loudspeaker produces a tone that informs the experimenter of the amplitude and frequency of the current waveform. Unlike simply attaching a speaker to the input and output of a passive circuit, this approach uses the speaker as the impedance element of the circuit. This can allow additional opportunities for student investigation and understanding.

Methods

Participant selection: Participants were enrolled in two universities, A and B: both small, private, midwestern universities with student bodies below 5,000 with predominantly white and male engineering enrollment and class sizes below 30. The experiment groups are summarized in Table 1.

Students performed a frequency sweep of a high-pass RC filter circuit. The control group students were assigned a version of the experiment using a discrete resistor, which produces no sensory output.

Table 1: Summary of intervention groups

Location	Institution A		Institution B	
Experiment	Resistor only (control)	Speaker only	Resistor first, speaker second	Speaker first, resistor second
N	18	16	9	7
Assignment time	Homework assignment, submitted after 1 week		2.5 hour lab, submitted at end of lab	
Previous circuits instruction	23 weeks		19 weeks	
Previous filter Experience	Build of filter circuit in previous circuits class (some with transducer). In-class coverage of filter properties and terminology.		Simulation and build of filter previous week (no transducer). Cutoff frequency and highpass lowpass terminology defined during lab time and during lecture in the week following this lab..	

The intervention group did the same experiment with a loudspeaker (see Figure 1). Since the resistor and speaker have similar resistance[1], the measured voltage transfer functions are similar, but the speaker produces sound as the frequency sweep progresses. Though simple, this experiment has many opportunities to make mistakes in wiring and instrumentation. In both experiments, students are expected to troubleshoot and correct those mistakes. The speaker experiment allows students to use sensory feedback to recognize and correct their mistakes- the loudspeaker makes an ascending tone when receiving power.

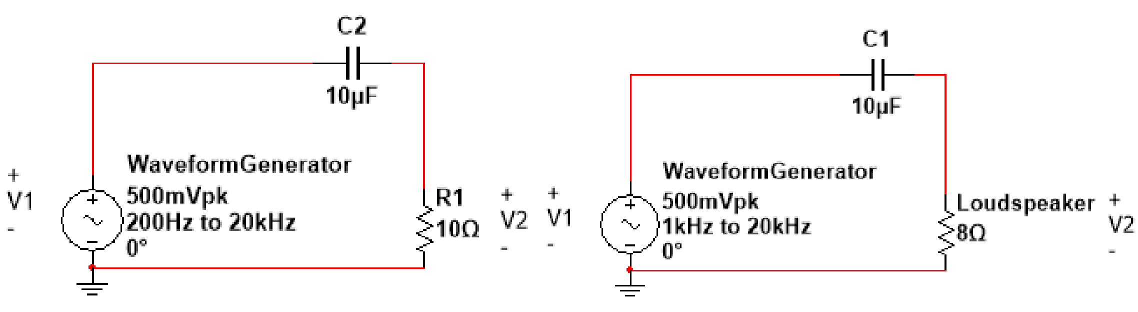

Figure 1: Circuits constructed in the control experiment (left) and intervention experiment (right)

[1] Loudspeakers have significant inductive and capacitive character near their mechanical resonance which is ignored in this experiment. Students at Institution A investigate the reactive nature of the speaker itself in an experiment later in the academic term.

After completing the experiment, students completed a survey with the four questions included below. The first question investigates whether the experiment was successful in advancing students' understanding of a frequency response. Two important attributes of the frequency response are the cutoff frequency and low/high pass characterization. As such, students were asked to determine those for the provided circuit. The goal of the final question is to assess whether students used the sensory feedback to debug their circuit.

Survey instrument:

1) After this exercise, my understanding of frequency response has grown…
   - ☐ I'm more confused than before
   - ☐ About the same
   - ☐ A little better
   - ☐ I understand much better
2) In the graph of your amplitude frequency response, indicate the location of the cutoff frequency.
3) Does your system display a low pass response or a high pass response? How do you know?
4) How do you know your circuit is working correctly? If you had experimental difficulties, how did you resolve them?

Findings

Both quantitative and qualitative evaluation of the impact of the speaker intervention experiment are summarized in this section.

<u>In the graph of your amplitude frequency response, indicate the location of the cutoff frequency.</u>
Student performance was overall poor on the question identifying the cutoff frequency in the graph from the frequency sweep as shown in Table 2. The audio feedback did not appear to help due to the variations in perceived loudness with frequency and gentle slope of the filter response.

Table 2: Portion of student responses correctly locating cutoff frequency

	R only	Speaker only	Speaker, Completed First	R, Completed Second	R, Completed First	Speaker, Completed Second
% correct	66%	46%	50%	50%	75%	60%

Overall, there was no clear difference in student understanding of cutoff frequency between groups. At institution A, students in both the speaker only and resistor only groups made instrumentation errors showing -50 dB responses indicative of a lack of good electrical connection. The results are not significant: for the observed differences, a sample size of 250 would be required to attain a statistically significant alpha value of 0.9. At institution B, students were generally successful obtaining the correct frequency response. However, they struggled to accurately quantify the cutoff frequency. In their responses, several students qualitatively described the point on the frequency response they were looking for, but did not provide a numerical answer. This is at least partially attributable to the fact that these students had not yet been presented with the theory of filter design or of frequency response. Compared to the week prior, students were largely more successful in obtaining an accurate frequency response.

After this exercise, my understanding of frequency response has grown…

Overall, students reported that their understanding stayed the same or grew slightly as shown in Table 3. The small N prohibits more detailed analysis of findings. In all groups, student understanding generally remained the same or increased. Students at institution B reported a greater increase in their understanding, which is likely attributable to the fact that this was the second lab on frequency response they were completing without the formal underlying theory.

Table 3: Student self report of growth of their knowledge of frequency response

	R only	Speaker only	Speaker, Completed First[2]	R, Completed Second	R, Completed First[3]	Speaker, Completed Second[4]
More confused	1	0	1	0	0	0
About the same	13	10	1	1	2	0
A little better	3	5	3	4	4	4
Understand much better	0	0	1	1	2	1

Does your system display a low pass response or a high pass response? How do you know?

Students displayed errors in identification and terminology that are anticipated for any laboratory experiment on frequency response. In their written reflections, some students correctly qualitatively described a highpass response, but incorrectly classified it as a lowpass response.

Students in both the speaker completed first and resistor completed first groups both emphasized the behavior of the speaker when justifying whether their circuit was high or low pass. One student in the resistor completed first group reversed their judgment of the filter nature after doing the speaker version of the experiment. After completing the resistor-only portion of the experiment, their description was that "*this is a lowpass response because the higher frequencies are being filtered out resulting in all the lower frequencies being heard*".

[2] Note that one student in this group did not submit their reflection questions.
[3] Note that one student in this group did not respond to this question.
[4] Note that four students did not complete the reflection questions after the second portion of the lab.

However, after completing the second portion of the experiment with the loudspeaker output, they revised their description to "*High pass response because all of the frequencies below 2.1 kHz were inaudible.*" Such responses are encouraging that the sensory feedback helps students gain intuition with classifying types of frequency responses.

Many students used the pitch/volume relationship observed in the speaker experiment to justify the selection of high or low pass response. Included below are indicative student responses demonstrating this:

- *"High pass. As frequency increases, output amplitude increases then levels off"*
- *"At higher frequencies, the gain of the speaker was higher. So this is a high pass response"*
- *"High pass, sound emitted when frequency increased"*
- *"The speaker was making a noise, and the plot showed amplitude which was proportional to speaker volume"*

Together, qualitative and quantitative observations support the use of the proposed experiment to foster student intuition.

<u>How do you know your circuit is working correctly? If you had experimental difficulties, how did you resolve them?</u>

This question had more divergence between the resistor and speaker experiment. Some students used the output of the speaker to debug their circuit as exemplified by the following response:

> "*Initially I was getting a really weird signal that had lots of jagged up and downs and no real trend. At first glance I thought it was just a noisy signal due to a loose breadboard as it was with the resistor circuit and was seeming to be a very flat response. Upon further examination, I realized that there was no noise [sound] from the speaker and the signal I was measuring was purely noise [unintentional signal].*"

Other responses indicate that students used the output of the speaker to validate their results, though that did not guarantee their ability to correctly interpret or act on that information:

- *"You know the frequency sweep is working because you hear a change in pitch as frequency gets larger"*
- *"We could hear it start at a low frequency and work all the way up until we couldn't hear it anymore"*
- *"I know the circuit part is fine, but I have no clue if the voltage measurements are correct because I can hear the speaker increase in pitch as frequency increases."*
- *"The speaker was making a noise, and the plot showed amplitude which was proportional to speaker volume."*

- *“All of the low frequencies were filtered out and only frequencies above 2.1 kHz were able to be heard.”*

Discussion and Conclusion

This study has a very modest number of participants so general conclusions are preliminary. However, there was a stark difference in students' justification of why they knew their circuit was working. The fundamental electronic principles of both experiments are nearly identical. Both groups made mistakes in instrumentation and terminology. However, only the speaker group used sensory feedback to detect errors. The student’s understanding that the speaker was a part of the circuit under test - in contrast to being peripheral to the circuit under test - may have motivated the use of sound as a diagnostic tool.

This result may not generalize to all inclusions of transducers in experiments. Many transducers such as strain bridges introduce many imperfections (common mode rejection, small parasitic resistances) that could distract the student from the fundamental circuit theory being taught. It is possible that the sensory feedback engages students in the laboratory by making it more entertaining, in addition to any concrete debugging benefit. Future work to more carefully examine the troubleshooting benefits should employ a think-aloud protocol with students explaining their debug process as the experiment proceeds, which could uncover student thoughts on troubleshooting that are hidden in an end-of-experiment reflection question. These qualitative studies are also more compatible with smaller student samples, as richer data is extracted from each student participant.

It did not appear that the audible response of the speaker aided in the determination of the specific cutoff frequency. The individual sensitivity of ears to modest changes of loudness - termed the *just noticeable difference* [*JND*] - of the tone at the cutoff (-3 dB) and the slow roll-off of a first order filter (-20 dB/decade) are suspected to be contributors to this result (Fastl, 2007).

The use of a sensory element (speaker) as a component of the circuit under test offers additional opportunities for both student learning and understanding. The specific ways in which a speaker differs from a resistor can be discussed - introducing the concepts of non-ideal components and non-ideal models. Speaker-specific characteristics like resonance could also be incorporated into the lesson.

To attain quantitatively significant results, the experiment must be repeated with a much larger number of students and more carefully scoped questions to demonstrate a reliable impact on quality of learning. A repeat study should use earbuds which have higher impedance, a less pronounced mechanical resonance, and isolate students’ audio from one another.

Future work could also study other types of sensory feedback such as vibration motors, temperature sensors, and piezo transducers. For audible feedback to be adopted as a best practice, accommodations for personal tonal sound sensitivity and/or the use of increased filter order may be both necessary and helpful. Many transducers are now small and inexpensive enough to be included in student laboratory kits as technology has miniaturized for mobile devices. It would also be interesting to explore similar experiments in later courses and later in the circuits course curriculum, to see how the effect of sensory feedback impacts student intuition as their technical expertise grows.

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