Exploring students' activities and learning in an analog electronics lab session

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INTRODUCTION

Many (introductory) engineering courses cover topics in which basic physics principles are applied or extended. It is therefore plausible that methods from Physics Education Research (PER) could be applied to investigate student understanding in these engineering courses. A lot of research in PER has focused on student difficulties with specific concepts in introductory physics and supports some general conclusions on teaching and learning of physics that by now are widely accepted [1-2]. More recently, there is a growing research interest in more advanced physics courses. However, for these courses the details of effective instruction, including effective (upper division) laboratory work, are not yet well known.

Analog electronics is a typical upper division lab course building on and extending principles covered in an introductory Electricity and Magnetism course. Although there is extensive research on conceptual difficulties with basic electric circuits, only little is known about student understanding of more advanced electronics concepts.

To get insight in *what* students actually learn and *how* and *under which conditions* they develop an understanding of concepts during the *lab* sessions of an upper division electronics lab course, we started an in-depth investigation of student learning during lab work.

In this paper, we focus on second year engineering students' learning in a lab session on passive *RC* filters. We will present results of student answers on

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conceptual questions that were administered as pre- and post-test and relate the results to the activities during the lab.

1 LITERATURE REVIEW

There is an extensive body of research on student understanding of electricity and electric circuits [e.g. 3-10 and references therein]. A substantial amount of this work has been carried out at the precollege level, but there also have been investigations in undergraduate courses, both for technical and non-technical careers. Most of the results so far focus on student ideas about DC circuits [3-6, 9-10], with only few studies about AC circuits [15-19]. However, we do expect some of the difficulties observed in this context to be also relevant for the understanding of more advanced electronics topics such as first order passive *RC* filters.

Possibly relevant concepts, and the corresponding student difficulties in DC circuits that have been identified, include:

Current: Students often confuse current with voltage and have difficulties with the physical interpretation of moving electrons. Current is frequently thought to be ‘consumed’ and students do not apply conservation of current [4, 17].

Voltage: Students have problems with applying Kirchhoff’s voltage law and think that there can be no voltage without current [4, 18-19].

Resistance: Students don’t seem to grasp the physical interpretation of a resistance, thinking more current means more resistance and confusing series with parallel. As a consequence, they have problems interpreting Ohm’s law [8, 17].

Sequential reasoning: Students fail to see the circuit as one entity. Instead, they analyse every component separately while ‘going around’ the circuit [3, 5, and 16].

Complete circuit: Students have no functional understanding of complete circuits [9].

Capacitance: Students have difficulties understanding the function of a capacitor and have problems reasoning on *RC* circuits qualitatively [10].

Recent research on more advanced AC sources shows that students have difficulties with phases, that they do not fully understand the physical meaning of the mathematical description and that they do not always understand the frequency dependence of the impedance [16-17]. Concerning more advanced electronics topics, only very little research has been published [11-14].

2 CONTEXT OF THE RESEARCH AND METHODOLOGY

2.1 Context of the study

Our sample included second year engineering students in 2 different electronics courses at 2 different university colleges of the KU Leuven Association. All students took the course as a compulsory part of their curriculum. Both courses consist of lectures and a substantial number of lab sessions. In each of the courses one lab session deals with 1st order passive *RC* filters: the students have to construct a Bodeplot (both gain and phase) of a physical circuit. Both colleges make the lab manual available to students well before the lab and require the students to hand in a report one week after the lab session. Around 15 students participated in every lab session, divided in groups of 2 or 3.

In college A, the lab session lasted for two hours. After a short introduction, students performed the measurements for either a high-pass or a low-pass filter. They were expected to simulate the circuit at home and to include the simulations in their report.

In college B, the lab sessions lasted for 3 hours. Students prepared for the lab by making an assignment. In the lab, they started with computer simulations before performing the experiments for both a high-pass and a low-pass filter.

2.2 Conceptual questions

Preliminary to this study, we conducted student interviews to get insight in undergraduate students' understanding of basic first order *RC* filters and we recorded several lab sessions of similar labs in 3 other colleges. Based on these results, five different questions on concepts related to *RC* filters were developed and administered as pre- and post-test before and after the lab session on filters. The participation in the tests was voluntary and did not affect students' grades. However, all students present in the session participated in the tests and seemed to make a genuine effort in answering the questions. All questions were open ended and students were asked to explain their reasoning as careful as possible.

87 pretests were administered at college A and 13 in college B, totaling 100 pretests. A few weeks later, post-tests were taken in both colleges: 74 students in college A and 11 students in college B participated, bringing the total number of post-tests to 85. As the students were asked to fill in their student-number, their pre- and post-tests could be matched individually. In total, 70 students filled in both tests and could be correlated. All numbers mentioned later on refer to the group of 70 matched students, unless specified otherwise.

Written answers on the tests were analysed to evaluate the student ideas and reasoning difficulties that we found in the interviews on a larger scale and to get a nuanced understanding of what it is that students understand reasonably well and what is problematic for them. We present results on three questions.

3 RESULTS

3.1 Signals

As we found in preliminary interviews that students only had limited understanding of multi-frequency signals [20], we explicitly asked students to draw a signal consisting of two frequency components on a given diagram and to label the axes.

In advance, we expected students to draw a sine wave with high-frequency noise added to it (as in Fig. 1), and some students (5 in the pre-test and 18 in the post-test) indeed did so. A couple (2 pre and 6 post) used a frequency-domain representation and 16 students made a (more or less correct) sketch like the one in Fig. 2 in the pre-test, 17 did so in the post-test. However, looking at the corresponding answers in the post-test suggests that students drawing a signal like in Fig. 2 might not completely understand what is meant by a signal consisting of two frequencies, as several of them used one of the wrong representations in the post-test, while this was not the case for students that sketched a noisy sine. 46 and 30 students gave no answer or a wrong one in the pre- resp. post-test. The different errors that students made include sketching a signal with only 1 frequency component, 2 overlapping signals (Fig. 3) and a signal which has 2 frequencies at different times (Fig. 4). Some even showed a sketch of the Bodeplot of a low-pass or high-pass filter (5 in total), clearly indicating that they have no idea what is being asked. 21 students gave no answer in the pre-test while we got 10 blank copies for this question in the post test.

As mentioned earlier, most students who sketched a noisy sine in the pre-test did the same in the post-test or switched to a frequency-domain representation. The ones that first made a frequency-domain representation, stuck to it in the post-test, while those drawing a signal such as the one in Fig. 2 can be divided into 3 groups: those that stuck with it (9), those that switched to a noisy sine (3) and those that made a wrong sketch in the post-test (5). Most of the 21 students who improved their answer (to a noisy sine, a frequency domain representation or a signal like in Fig. 2) didn't fill in this question in the pre-test (13). Also, 8 students who originally sketched one of the options of Fig. 3 and Fig. 4 or a Bodeplot showed an improvement, although most (25) stuck to their original (wrong) answer, switched to another wrong answer or didn't fill in the question. Of this group, none of the 8 students that originally sketched a sine with one frequency showed any improvement: 4 didn't fill in this question in the post-test, 3 switched to two overlapping signals of Fig. 3.

Figure 1: A noisy sine wave

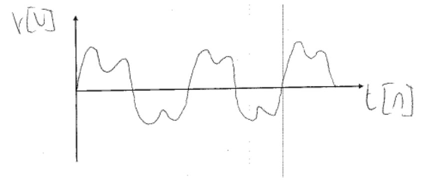

Figure 2: A more or less correct signal

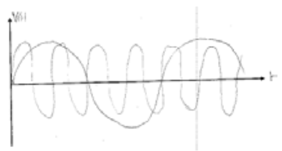

Figure 3: 2 overlapping signals

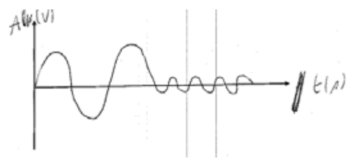

Figure 4: 2 signals shifted in time

Phase shift

The second question probes for understanding of a phase shift. Earlier results [16, 20] revealed that students have trouble with or do not take into account the phase shift between input and output voltage of *RC*-filters. This question showed a graph of a simple sine wave with the following question: *"A time-dependent signal is shown on the figure below. Draw, on the same figure, a signal that leads the given one by 90°."*

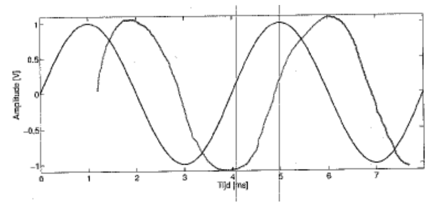

Figure 5: Negative phase shift by starting at t > T/4

From both the pre- and post-test, it is clear that students have a reasonably good understanding of what is meant by a 90° phase shift, since most (56) indeed drew a 90° phase shift. 14 students sketched a signal that had a 180° phase shift in the pre-test, although most of them managed to draw a 90° phase shift in the post-test, resulting in a total of 67 students.

What is not well understood by the students is the *direction* of the phase shift. Of the group drawing a 90° phase shift in the pre-test, 40 out of 56 (71%) managed to draw a correct positive phase shift. In the post-test, when asking to draw a lagging signal, 45 out of 67 (67%) had the direction right. What is most interesting, however, is that of the group who originally used the correct direction, a big subsection (9 out of 40) used the wrong direction in the post-test. These two elements point to a general understanding of the concept of a phase shift, although the sign or direction of the phase shift seems less well understood. In 22 of the total 185 copies students only started to draw their signal at *t* > *T/4* of the original signal, as shown in Fig. 5. We suspect this points to students thinking about a phase shift as an actual shift in time. This is not wrong per se, but they do seem to think it stems from one signal starting later in time rather than two signals starting at the same time, but at a different point of the cycle.

3.2 Understanding of a basic high-pass filter

In this question, students were asked to rank several high-pass *RC* filters in order of decreasing output voltage. The filters varied in the values of the *R* and *C* component, but had the same (AC) input signal. The exact formulation of the question is in Fig. 6.

Question V
The circuits below all have the same AC-voltage (finite amplitude and finite frequency) as input signal. However, the values of the resistors and capacitors in all circuits are different. The parameters R and C are equal everywhere. Rank the circuits, from greatest to least, on the basis of the amplitude of the output voltage. Indicate explicitly if the output voltage is zero or if the output voltage is equal in two situations. Explain!

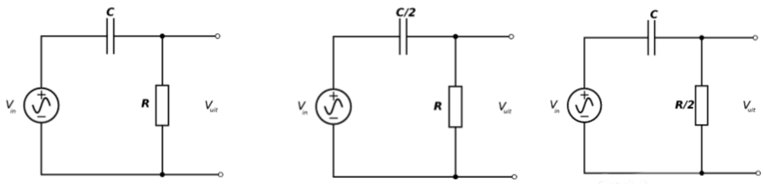

Figure 6: Question asking to rank several high-pass filters

This question can be answered in two ways: either by recognizing the circuit as a high-pass filter and reasoning on the cut-off frequency or by looking at it as a voltage divider. We asked this question because of this variety of methods to arrive at the solution: it could be interesting to see how students look at this circuit before and after a laboratory session.

Many of the answers were incomplete, only showing the result without an explanation, making it hard to interpret the mistakes students made. This might be related to the question being the last one in the test. There were 12 students who didn't fill in the question at all in the pre-test and 11 in the post-test. In some cases, the specific answer gives a clue on the type of error, but to a large extent this is rather subjective as it is not explicitly clear from the data.

The answers of the students are not accurate at all: only 2 students manage to formulate a correct answer in both the pre- and post-test. A big majority (11 out of 13) of students answering the question correctly in the pre-test (mostly without explaining) answered it wrongly in the post-test. About the same number of students did the opposite, showing an improvement (10 out of 57).

Only one student correctly used the cut-off frequency to find the solution in the post-test. He explicitly recognizes a HPF and states "*freq = 1/(2πRC) => circuit A has the lowest freq so the highest ampl.*" Nobody used this approach successfully in the pre-test, although 4 others (2 in the pre-test and 2 in the post-test) attempted to do the same, but failed to arrive at the right conclusion. These latter students assumed that when the cut-off frequency decreases, also the output frequency decreases: "*They are all high-pass filters. The cut-off frequency = 1/(2πRC) => in B and C the cutoff is equal, so the same signal will exit. In A, the cutoff is only half, so smaller signal*". This shows that they don't have a clear understanding of what this cut-off frequency is.

Most of the other incorrect answers providing an explanation use one or another form of reasoning via a voltage divider or, more general, via Ohm's law and KVL:

3 students in the pre-test and 4 in the post-test claimed that the output voltage only depends on the value of the resistor, one even claiming the "*capacitor only induces a phase shift*", while another one seems to voice the general problem more clearly, saying "*V_{out} is proportional to the value of R for the same input signal*". This student might have understood Ohm's law correctly, but fails to apply KVL to take the capacitor into account.

Others (3 in the pre-test and 2 in the post-test) thought that "*only the capacitance has an influence on the amplitude, the resistor doesn't.*" They cited various reasons, including "*smallest amplitude is due to the smaller capacitance, for the other two it doesn't matter (higher current doesn't make a difference)*".

Yet another mistake made when using a voltage divider is either implicitly or explicitly assuming that the impedance of the capacitor is directly proportional to its value, while it is inversely proportional. This happens 4 times in the pre-test, but is more clear during the post-test, which contained one filter with values *C* and *R* versus one with *2C* and *2R* as values for the capacitor and resistor respectively. The students who thought the output voltage for these two circuits was equal probably assumed that the impedance of the capacitor doubled as well. 3 students explicitly made this mistake in their explanation and 11 implicitly (taking all 180 copies into account). These students arrived at the wrong answer despite understanding a voltage divider.

4 DISCUSSION AND FURTHER RESEARCH

The detailed investigation described in this paper has revealed that a significant number of students enter and leave a lab session with a lack of (conceptual) knowledge related to the topic dealt with during practical work. Results of the first question show that – after the lab - 41% of all 85 students have no idea of a real-life signal, and only 27% of the students relate a signal with two frequencies to a noisy signal. 21 students gave an incorrect answer in the pre-test but a correct one in the post-test. We consider this an important issue as this is related to the core use of a filter. However, a detailed study of the lab manuals shows that in none of the activities students are confronted with this kind of signals; they only work with pure sinusoidal signals.

The second question relates to the understanding of a phase shift. Although most students seem to know what is meant by a phase shift, 22 students draw – after the lab - a phase shift of 90° in the wrong direction. This somehow came as a surprise as students had to measure phase shifts during the lab and in both colleges, the measurements were done using an analog oscilloscope. The video material of the actual activities during the lab sessions however shows that students often disregard the sign of the phase shift completely, only later adjusting it when they realise it "*should be negative [positive], because it is a low-pass [high-pass] filter*".

The third question deals with the impact of the different components in the circuit on the output signal. The large number of students providing a ranking without explanation suggests that they have difficulties explaining their reasoning. The fact that almost no students are cued to explain their reasoning based on the cut-off frequency of the filter after doing a lab where they had to determine this cut-off frequency for a real circuit is astonishing. We expected students to reason on the circuit as a voltage divider before the lab and to change their reasoning using the cut-off frequency after writing their report, but this seems not to be the case. Instead, a lot of students were not able to explain their reasoning. The written explanations we got suggest that impedance of a capacitor is not well understood and confront us with students still experiencing difficulties mentioned in the context of DC circuits like local reasoning.

The evidence from this investigation confirms and extends earlier findings that lectures and laboratory experiences are not always sufficient to help students to develop a rich and detailed understanding of the concepts that are dealt with and that basic difficulties with electrical circuits often persist even after advanced instruction [9, 13]. The results have relevance for teaching staff in that it might make them aware of the need for a careful design of lab activities that explicitly focus on topics that are difficult for students to grasp. Future research will consist of development and testing of modifications in the lab activities in order to optimize student learning during labs.

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