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The Importance of Introducing the OCTC Method to Undergraduate Students as a Tool for Circuit Analysis and Amplifier Design

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Abstract: The open-circuit-time-constant (OCTC) method is an approximate analytical computationally simple approach applicable to baseband amplifiers and cascades of them. It has a dual purpose: a) to estimate the dominant pole, and the −3dB bandwidth frequency, and b) to identify actual or parasitic component values primarily responsible for this bandwidth guiding the designer in optimizing component values and circuit architecture. The present study focuses on the teaching of OCTC and the analysis of students' depth of understanding. The OCTC module is part of the course "Electronics III" aimed towards advanced undergraduate students who are asked to solve two sets of problems analytically and simulate the circuits using LTspice and compare the results. The paper discusses students' misconceptions and the evaluation of students' performance via assignment grades, an anonymous sampling test and final exams (four exams during two academic years). A quantitative evaluation of the students' perspective of the course is also presented based on two anonymous surveys, at the beginning and the end of the semester. According to the evaluation results, the proposed way of introducing the OCTC method along with the simulation exercises was beneficial for the students and improved their academic performance and attitude towards the course.

Keywords: OCTC; −3dB frequency; bandwidth; amplifiers, LTspice; misconceptions; circuit analysis; amplifier design

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1. Introduction

The open-circuit-time-constant (OCTC) method is an easily applied technique to estimate an approximation of an amplifier's bandwidth. The importance of the method lies not only in the fact that it gives a low-error approximation of the f_{3db} first Bode diagram (dominant) pole-frequency by just applying a relatively simple algorithm but also in its capability to provide appropriate information on the major causes that limit the amplifier's bandwidth. This is such an important advantage that overtakes the usefulness of frequency response (ac) simulation, since the clues OCTC provides can be used as an effective tool for a large variety of amplifier types [1–3]. This article is an extended version of the paper already published in MOCAST 2019 proceedings.

The significance of the OCTC method briefly described above leads us to utilize it as one of the most essential chapters in educational electronics. The undergraduate electrical and electronic engineering students have to deeply understand the OCTC algorithm process and take advantage of it at upper-level courses, when they will be asked to design their first amplifiers with specific properties. This will contribute to their experience as electronic engineers and their post-graduation professional or academic course.

In order to be able to deeply understand and properly apply OCTC when asked (circuit analysis) or needed (circuit design), the undergraduate students need to have a strong background in electronics. This a-priori knowledge and experience includes basic circuits and systems analysis (transient and steady-state node/loop method application), mathematical formulas (common differential equations and Laplace transform), BJT and MOSFET transistor DC and AC properties and basic DC supply and identification and analysis of amplification stages. In the Department of Electrical and Computer Engineering of National Technical University of Athens (NTUA), those subjects are covered by the "Introduction to Circuit Analysis", "Introductory Electronics and Telecommunications Lab", "Electronics I", "Electronics II" and "Circuit and Systems Theory" courses, being taught during the three first years of the bachelor degree program. The OCTC method is taught at the "Electronics III" course during the fourth bachelor degree year (7th semester) and it is expected that the students already have basic experience in the electronic analysis field. We choose this specific subject because OCTC is a basic part of the course "Electronics III" and in addition is a great example of a design tool for electronics. The OCTC method as a tool for circuit analysis and amplifier design enables students to test and repeat basic electronics knowledge while at the same time understanding the utility of approximate evaluations of electronic circuit behavior. It is also a topic offered for comparison between simulation and analytical-approximation solution.

As university educators, we have been teaching "Electronics III" as an optional course, enrolled by students that wish to follow a discrete electronics or analog IC designer path, for the last five years. In the last three years, the course grading policy has been changed by adding an LTspice simulation lab, in order to assist the students to better understand how the theoretical methods being taught are linked to some basic applications as well as taking their first steps as electronic designers.

The OCTC method is a mandatory part of this educational process. However, teaching experience has shown that the students have a characteristic difficulty in understanding and applying it even when they are asked to in simple quizzes. The main causes do not appear to stem from a misunderstanding of the algorithm process itself as someone would expect. Instead, we have revealed that an important percentage of them actually apply OCTC whilst lacking fundamental amplification stage analysis knowledge that could really simplify the overall procedure. It was observed that when they apply OCTC, they prefer writing complex equation systems to compute each parasitic capacitor's impedance, leading them to mistakes. Exam problems or exercises of finding equivalent resistance are solved by many students in an unnecessarily complicated way. This is because they have not embodied or learned to use known step-by-step properties as key tools. On the other hand, there is often a question of whether the students understand the usefulness of the OCTC method as a design tool, because they see it as a method to be applied only when asked for as part of an exercise.

The purpose of teaching this module is to alleviate the above phenomena. This can be done using teaching techniques such as frequent reminders of the basic tools, encouraging the use of amplifier properties, explaining design problems and using simulations. It has been observed that the students tend to address electronic circuit problems in a rather local and sequential way with no reference to the appropriate principles, rules, and methods. A frequent reminder of the basic tools taught in previous semesters is important.

It is helpful to encourage the use of amplifier properties through examples, the first step by step and then as a complete application. Memorization of specific circuits, gain formulas, and key results may play a crucial role in students' ability to successfully solve typical amplifier circuits. The findings from the teaching feedback suggested that many students likely did not possess a robust understanding of the behavior of different basic amplifier circuits, even after instruction on basic circuits has been completed (in previous semesters). For this reason, we were interested in developing a task in which students would be forced to think deeply about the currents and voltages in typical amplifier circuits.

We believe students need to be actively engaged in the learning process in order to start thinking about the way amplifier circuits work and start constructing their knowledge from their own quantitative observations. Design problems, either as exercises to be solved or at the laboratory level can be very helpful.

Using in teaching process simulations (e.g., LTspice, Pspice etc.) with changing parameters and examples of applications is a good way to bridge the gap between theoretical-analytical and design-practical.

Students learn when they are actively engaged in their class activities. To integrate theory with practice there will be a series of practical laboratories such as the use of simulations. Simulation tools enable instructors to introduce complex configurations which can be easily tested by the students. Perhaps contrary to common belief, this development calls for a deeper understanding on the part of the students as a prerequisite for smart and efficient use of simulation. Furthermore, analytical comprehension of basic concepts and strategies is indispensable for good circuit design. A proposal for this is assigning problems to students that depart from the classical theoretical motif we used to in the previous years.

The method of teaching students is very important. The teacher should be very patient in teaching and should move slowly from one idea to another one. What is needed is a combination of lectures, tutorials, laboratory exercises (hands-on and simulations) and projects.

Applying the above, we saw that students' grades significantly improved in the final exam, while the number of students taking the course Final exams increased from 105 to 120 students. Furthermore the number of students who take the optional "Analog VLSI design" course in the semester after "Electronics III" has increased from 15 to 40.

The remainder of this paper is organized as follows. Section II describes the OCTC method principles and outlines some useful analysis tools. It also presents some examples given to the students and some of their misconceptions regarding OCTC. Furthermore, a sampling test given to the students is described. In Section III, the results of the students' performance in assignments, recent final exams and their answers in the sampling test and two surveys are demonstrated and discussed in Section IV. Finally, Section V concludes this work.

2. Materials and Methods

In this section, the OCTC formula is briefly described. Furthermore, the teaching methodologies applied are presented for both the classical, "by hand" circuit analysis and the simulator-based one following an explanation of how those tools could contribute to the preparation of the students for their first design project.

2.1. OCTC Method

2.1.1. OCTC Principles

The OCTC or zero-value time-constant analysis [4,5] is an approximate method to estimate the dominant pole (and thus the −3dB frequency) of baseband amplifiers. The basis of the method is the approximation that the −3dB frequency of the amplifier is determined by the dominant denominator term of its transfer function. This approximation can be inaccurate in cases where a zero in the numerator is near the frequency of the aforementioned pole. The method employs a simplified way for finding the first-order approximation by summing the RC-products (Resistor-Capacitance) for each capacitor in the circuit. The resistance R for a selected capacitor is the resistance seen by it when all other capacitors are removed. All of the decoupling and AC-coupling capacitors are effectively short circuits. For any circuit we can derive a transfer function F(s) by means of small-signal analysis that has the general form [6].

$$F(s) = A\frac{(1-\frac{s}{z_1})(1-\frac{s}{z_2})...(1-\frac{s}{z_m})}{(1-\frac{s}{p_1})(1-\frac{s}{p_2})...(1-\frac{s}{p_n})}$$
$$F(s) = A\frac{1-s(1+\frac{1}{z_1}+\frac{1}{z_2}+...+\frac{1}{z_m})+H.O.T.(s)}{1-s(1+\frac{1}{p_1}+\frac{1}{p_2}+...+\frac{1}{p_n})+H.O.T.(s)}$$
$$F(s) \cong A\frac{1-s(1+\frac{1}{z_1}+\frac{1}{z_2}+...+\frac{1}{z_m})}{1-s(1+\frac{1}{p_1}+\frac{1}{p_2}+...+\frac{1}{p_n})}$$

$$F(s) \cong A\frac{1}{1-\frac{s}{p_1}}. \quad (1)$$

Higher order terms (HOT) of s can be neglected assuming circuit operation in relatively low frequencies. A crucial assumption is the existence of a dominant pole, at a much lower frequency than any other pole or zero

$$|p_1| \ll |p_2|, |p_3|, ..., |p_n|, |z_1|, |z_2|, ..., |z_m| \quad (2)$$

The dominant pole can then be approximated by

$$p_1 \cong -\frac{1}{T}, \quad (3)$$

where the total time constant T is expressed as

$$T = \sum_{i=1}^{n} \tau_i \quad (4)$$

and $\tau_i = R_{C_i}C_i$, $i = 1, 2, \ldots, n$ is the time constant of the ith capacitor and R_{C_i}, $i = 1 \ldots n$ is the effective (Thevenin) resistance across the terminals of the ith capacitor with all of the other capacitors (parasitic and intrinsic device capacitances) removed (open-circuited) and all of the biasing and coupling capacitors short-circuited in the small signal model of the circuit. So, the -3dB frequency is

$$f_{-3dB,OCTC} \cong \frac{1}{2\pi T}. \quad (5)$$

OCTC is a quick method for an approximate calculation of the -3dB frequency (usually a pessimistic evaluation). It is also a quick way for finding which one of the R, C and g_m are "responsible" for the low value of the -3dB frequency (low bandwidth). The method is a kind of "design tool" and not a method for final calculations. It is used if the circuit has resistors, capacitors, and dependent sources. OCTC "works" well in the analysis of amplifier chains (cascades) or multistage amplifiers. OCTC is not reliable if the transfer function has no dominant pole or has zeros (in relatively low frequencies). Also, the method is not reliable if there are parallel paths for the signal to follow, or if there are inductors in the circuit.

2.1.2. Applying the Method

Consider an arbitrary linear network comprised only of resistors, voltage and current sources (independent or linearly dependent) and capacitors. To apply the OCTC method, the small-signal model of the circuit should be derived (including the parasitic capacitances of the transistor models). The steps for the calculation of $f_{-3dB,OCTC}$ are described below:

1. Select the i-th capacitor, C_i, and remove all others. All decoupling and AC-coupling capacitors should be short-circuited.
2. Set all independent sources to zero (i.e, short-circuit all independent voltage sources and open-circuit all independent current sources).
3. Find the resistance R_{C_i} seen by the ith capacitor. This can be done either by inspection or by replacing C_i with a test current source I_x, determining the voltage V_x at its terminals, and calculating $R_{C_i} = V_x / I_x$, (or, equivalently, by applying a voltage source V_x and finding the current I_x drawn from it).
4. Repeat steps 1–3 for $i = 1, 2, ..., n$.
5. Calculate T using (4).
6. Calculate the -3dB frequency using (5).

The OCTC method typically gives a conservative estimate of the -3dB frequency. The dominant term in (4) corresponds to the pair of $R_{C_i}C_i$ which limits the overall bandwidth [4].

2.2. Useful Analysis Tools

2.2.1. Small-Signal Equivalent Circuit—A Frequent Form

The open-circuit time-constants for the circuit are determined by calculating the resistance seen by each capacitor between its terminals. Significant effort can be saved by recognizing that during an OCTC analysis some capacitors result in configurations similar to Figure 1. The resistance R is

$$R_{C_\mu} = R_A + R_B + g_m R_A R_B. \tag{6}$$

Resistances R_A and R_B may be actual, or equivalent, representing the total resistance seen at the corresponding nodes.

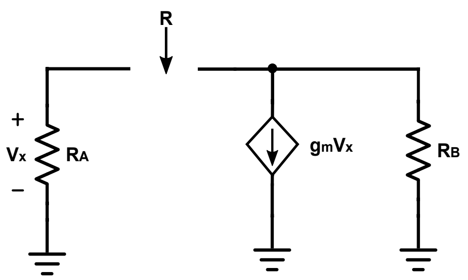


Figure 1. Similar configurations of some capacitors in OCTC analysis.

2.2.2. Miller Effect

The Miller effect accounts for an increase in the equivalent input capacitance of an inverting voltage amplifier due to the amplification of capacitance between the input and output terminals. Although Miller effect normally refers to capacitance, any impedance connected between the input and another node exhibiting high gain can modify the amplifier input impedance via the Miller effect [4]. This increase in input capacitance is given by

$$C_M = C(1 - A_v), \tag{7}$$

where A_v is the gain of the amplifier and C is the feedback capacitance. The Miller effect is a special case of Miller's theorem and applies to any impedance, not just a capacitance. A pure resistance or pure inductance will be divided by $1 - A_v$. In addition, if the amplifier is non-inverting then a negative resistance or inductance can be created using the Miller effect [6].

It is also important to note that the Miller capacitance is the capacitance seen looking into the input. If looking for all of the RC time constants (poles) it is important to also include the capacitance seen by the output. The capacitance on the output is often neglected. However, if the amplifier has a high impedance output, such as if a gain stage is also the output stage, then this RC can have a significant impact on the performance of the amplifier.

The impact of the Miller effect is often reduced by using a cascode or cascade amplifier rather than a common emitter. For feedback amplifiers the Miller effect can actually be very beneficial since stabilizing the amplifier may require a capacitor too large to practically include in the circuit, typically a concern for an integrated circuit where capacitors consume significant area.

In analog amplifiers, the curtailment of the frequency response is a major implication of the Miller effect. For example, the frequency ω_{3db} such that $\omega_{3db} C_M R_A = 1$ marks the end of the low-frequency response region and sets the bandwidth or cutoff frequency of the amplifier. It is important to note here that the effect of C_M upon the amplifier bandwidth is greatly reduced for low impedance drivers ($C_M R_A$ is small if R_A is small). Consequently, one way to minimize the Miller effect on bandwidth is to use a low-impedance driver. An example of that would be interposing a voltage follower stage between the driver and the amplifier, which reduces the apparent driver impedance seen by the amplifier.

2.2.3. Knowledge of Basic Amplifier Stages

Students should be able to recognize and have all the necessary knowledge of basic amplifier stages: common emitter (CE), common collector (CC), common base (CB), common source (CS), common gate (CG) and common drain (CD). Students should be able to calculate the voltage gain, current gain, input resistance and output resistance of all these amplifier stage-topologies. The methods for finding the voltage gain and input and output impedance for the basic stages of amplifiers are supposed to be known. Students should be able to write the voltage gain as well as the input and output impedance of amplifiers, without drawing the circuit models. Also useful is the knowledge of some transistor pairing: CD–CS, CC–CE, CD–CE configurations, the Darlington configurations, CC–CB, CD–CG configurations.

2.3. Teaching Examples

The OCTC method was introduced to advanced undergraduate students at Electrical and Computer Engineering School, National Technical University of Athens (NTUA) during a full academic year. The students were in the fourth year of their studies (total five years) and attended the "Electronics III" course. This course contains a four-hour module on the "OCTC method". The number of students that participated in this study was one hundred fifteen (115). Here we present two practical examples which were given as homework problems. Students were asked to solve the two problems analytically with the classical way, by hand (as exam problems) and to simulate the two circuits using LTspice, comparing the simulation results with the theoretical results [7–10]. For the problems, the BJT parasitic capacitances computation formula was given:

1. Collector–base junction capacitance

$$C_\mu = \frac{C_{jc0}}{\left(1 + \frac{V_{CB}}{V_{OC}}\right)^m}$$

2. Emitter–base junction capacitance

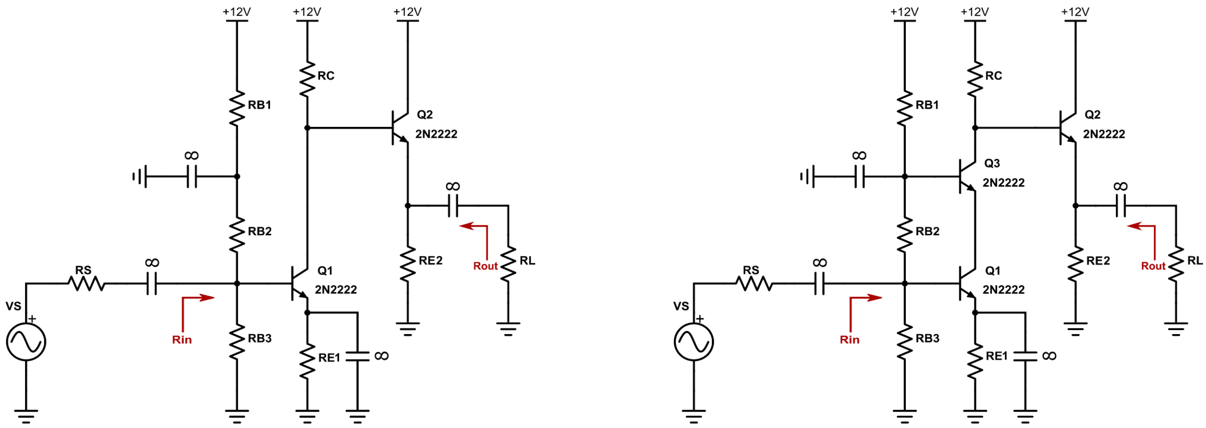
$$C_\pi = C_{de} + C_{je}.$$

where $C_{de} = \tau_F g_m$ and $C_{je} = 2C_{je0}$.

2.3.1. Problem 1

Consider the circuit in Figure 2a. Let $V_{BE} = 0.7V$, $V_T = 25$ mV, $R_{B1} = 30$ kΩ, $R_{B2} = 6$ kΩ, $R_{B3} = 12$ kΩ, $R_{E1} = 2.3$ kΩ, $R_C = 4$ kΩ, $R_{E2} = 1.8$ kΩ, $R_S = 1$ kΩ and $R_L = 1$ kΩ. The problem's questions were:

1. Find (try to answer) directly what impedance every node "can see" (without drawing an AC equivalent circuit).
2. For the BJT 2N2222 assume: $\beta = 200$, $C_{jc0} = 8pF$, $V_{OC} = 0.7V$, $m = 0.3$, $C_{je0} = 25pF$, $\tau_F = 400ps$. Ignore the Early phenomenon ($r_o \rightarrow \infty$). Applying the OCTC method estimate the high 3dB frequency $f_{-3dB,OCTC}$ and so the bandwidth of the amplifier.
3. Using LTspice for circuit simulation, sketch the Bode plot of the amplifier for the frequency range from $1Hz$ to $500MHz$. Determine the high 3dB frequency f_{-3dB} and so the bandwidth of the amplifier.



(a) Problem 1 **(b)** Problem 2

Figure 2. Schematics of the BJT amplification stages: (**a**): Problem 1. (**b**): Problem 2.

2.3.2. Problem 2

Modify the circuit in problem 1, adding the Q_3 BJT as in Figure 2b. Let $V_{BE} = 0.7$V, $V_T = 25$ mV, $R_{B1} = 30$ kΩ, $R_{B2} = 6$ kΩ, $R_{B3} = 12$ kΩ, $R_{E1} = 2.3$ kΩ, $R_C = 4$ kΩ, $R_{E2} = 1.8$ kΩ, $R_S = 1$ kΩ and $R_L = 1$ kΩ. The problem's questions are the same as in Problem 1 above.

The actual purpose of these two problems is firstly to allow the students to practice finding the f_{-3dB} via the OCTC method. Secondly, the problems focus on comparing the bandwidth calculated with the actual one (determined through the LT Spice AC simulation) and understanding the validity and operation of the OCTC method. In addition, the students come across a minor design task: to increase the amplifier's bandwidth by adding a cascode amplification stage. Furthermore, the problems serve to remind the students of basic amplifier analysis techniques.

The students should be able to predict what they see in the simulation results. If there is a discrepancy in the results, when simulation/lab results are different from what they calculated, students should also be able to answer why this is happening. This is a way to verify the understanding of concepts.

2.3.3. Solutions and Simulations

For each problem, students begin by performing a DC analysis on each circuit and then calculate V_{CB} and g_m. So they are able to determine the value of C_μ and C_π.

For Problem 1, the results of the analytical solution with the classical way (by hand) are the following (for each corresponding BJT) and the RC time constants are shown in Table 1.

Table 1. *RC* time constants for the first problem.

Q_i	$C_{\mu i}$ (pF)	$C_{\pi i}$ (pF)	$R_{C_{\mu i}}$ (Ω)	$R_{C_{\pi i}}$ (Ω)	$R_{C_{\mu i}} C_{\mu i}$ (ns)	$R_{C_{\pi i}} C_{\pi i}$ (ns)
1	4.25	65.62	109.41×10^3	691.95	465.11	45.41
2	4.52	114.70	3.88×10^3	42.69	17.55	4.90

The OCTC frequency was calculated from (4) and (5) $f_{-3dB,OCTC} = 298.62KHz$, whereas the SPICE simulation showed a frequency $f_{-3dB,Sim} = 327KHz$. As expected, the estimated -3dB frequency applying the OCTC method is close to the value that gives the LTspice simulation. In this example, the major limitation on the circuit frequency response comes from the time constant associated with the collector-base junction capacitance $C_{\mu 1}$ of Q_1, due to the Miller effect.

For Problem 2 the corresponding results are shown in Table 2:

Table 2. *RC* time constants for the second problem.

Q_i	$C_{\mu i}$ (pF)	$C_{\pi i}$ (pF)	$R_{C_{\mu i}}$ (Ω)	$R_{C_{\pi i}}$ (Ω)	$R_{C_{\mu i}} C_{\mu i}$ (ns)	$R_{C_{\pi i}} C_{\pi i}$ (ns)
1	6.38	65.37	1.41×10^3	693.40	9.01	45.33
2	4.54	115.09	3.88×10^3	42.45	17.60	4.89
3	4.62	65.30	3.88×10^3	26.02	17.95	1.70

We calculated $f_{-3dB,OCTC} = 1.65MHz$, whereas SPICE showed $f_{-3dB,Sim} = 2.4MHz$. Here the estimated -3dB frequency applying the OCTC method differs significantly to the value that gives the LTspice simulation. In this example, the time constant associated with the emitter-base junction capacitance $C_{\pi 1}$ of Q_1 are the major contributor to the -3dB frequency of the circuit.

2.4. Student Misconceptions

The term "misconception" is used to describe a situation in which students' ideas on a concept differs from the scientifically accepted [9,11]. In this study, we identify students' misconceptions and the typical errors they commit in answering questions and solving problems within the OCTC method. We report our findings on students' understanding of the fundamental topics involved in the study of the OCTC method. The following are the most important.

1. Miller effect and open circuit time constant (OCTC) method. Students have difficulties recognizing and applying the Miller effect for a capacitance.
2. Some students believe that the largest capacitor of the (transistors' capacitances) has the greatest contribution in defining the upper cutoff frequency.
3. Coupling and bypass capacitors in OCTC method. "Why don't coupling and bypass capacitors contribute to the definition of the amplifiers' upper cutoff frequency?" is the basic question. OCTC method approximately defines the upper cutoff frequency of an amplifier. It is used for high-frequency response of an amplifier. Upper and lower cutoff frequencies that define the bandwidth of an amplifier are often of greater interest than the complete transfer function. Coupling and bypass capacitors determine the lower cutoff frequency, whereas transistor (and stray) capacitances determine the upper cutoff frequency. Coupling and bypass capacitors are relatively large in value and their large impedances at high frequencies can be neglected. Thus coupling and bypass capacitors determine an amplifier's low-frequency response. Transistor capacitances are relatively small in value and their large impedances at low frequencies can be neglected.
4. What do we mean by "capacitors can be ignored"? Ignoring capacitors means that we operate at either a high enough or at a low enough frequency such that capacitors become either open or short circuits, leading to a "resistive" circuit. Note that the circuit is modified by the presence of the capacitors (e.g., elements may be shorted out). Capacitors typically divide into two groups:

low-f capacitors (setting f_L) and high-f capacitors (setting f_H). We need to identify low-f and high-f caps. We will use absolute limits of $f = 0$ (all capacitors open) and $f = \infty$ (all capacitors short) for this purpose.

5. The role of bias circuits. For DC bias ($f = 0$) all caps are considered as an open circuit.
6. Non-symmetrical differential amplifiers. For a symmetric circuit, differential and common-mode analysis can be performed using "half-circuits". Using "half-circuits" works only if the circuit is symmetric. Not all difference amplifiers are symmetric. Look at the load carefully. We can still use the "half-circuit" concept if the deviation from perfect symmetry is small. However, we need to solve both half-circuits.

2.5. A Sampling Test

An anonymous sampling test in the form of a questionnaire-survey relating to the students' perspective on the course was administered, at the beginning of the semester (see Appendix A) after teaching the OCTC method. The number of students participating in this study was 82 advanced undergraduate students at the Electrical and Computer Engineering School, National Technical University of Athens (NTUA). The questions of the questionnaire were the following:

1. Question 1: the MOS amplifier circuit displayed in Figure 3 is given. What is the computation relation, according to the circuit elements, of $R_{C_{gd}}$?

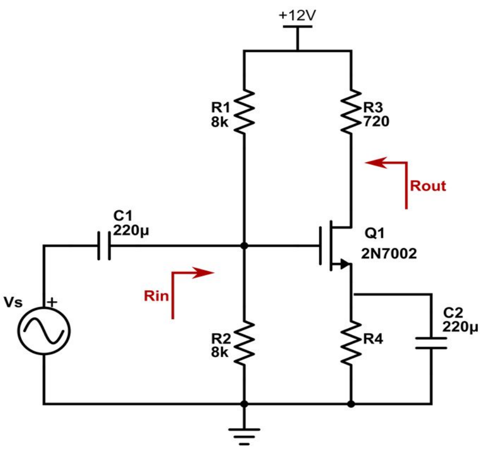


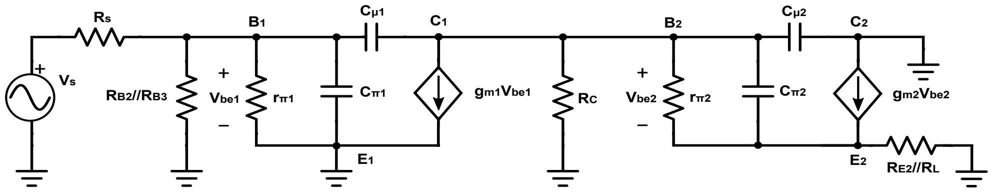
Figure 3. Schematic of the MOS amplifier circuit given in question 1.

2. Question 2: the equivalent signal circuit of a two stage BJT amplifier, displayed in Figure 4a is given:

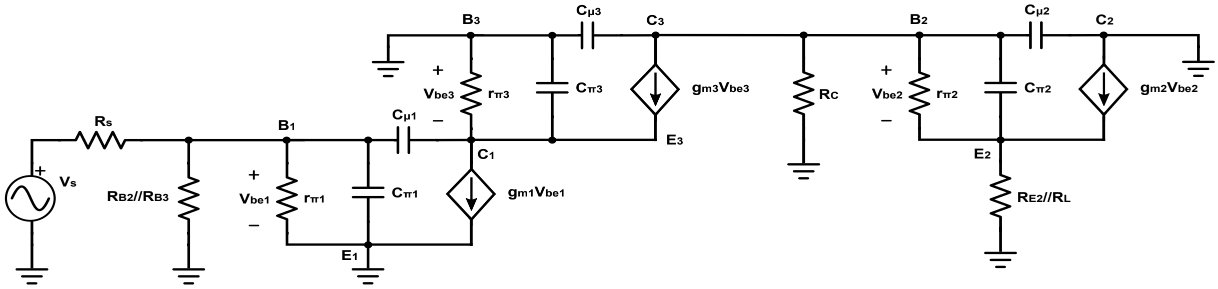
   (a) Find $R_{C\mu 1}$.

   (b) Which of the capacitances $C_{\mu 1}$, $C_{\pi 1}$, $C_{\mu 2}$ and $C_{\pi 2}$ do you think has the greatest impact on limiting the amplifier bandwidth and why?

   (c) What circuit modification can you propose to reduce the impact of the capacitance you selected in question (c)?



(a) Problem 1



(b) Problem 2

Figure 4. AC equivalent circuits of the amplification stages used in the two problems: (**a**): Problem 1. (**b**): Problem 2.

Students were instructed by means of conventional classes, laboratory simulations, and an e-class platform.

3. Results

3.1. Students' Performance—Homework Problems

In this section, the students' performance on homework problems, sampling test, final exams and quantitative evaluation are discussed [8,10,12,13]. Out of the 115 students, 82 (70%) answered Problem 1 correctly. The wrong calculation of the resistance seen across the terminals of the capacitors (Figure 4) was the main mistake of those who answered incorrectly. This was due to deriving an incorrect small-signal equivalent circuit initially (7% of the students), or incorrect equivalent circuit transformations during steps 1–4 of the OCTC method (15% of the students) and wrong mathematical calculations at steps 5–6 (5% of the students).

In Problem 2, 63 students (a little over 50%) answered correctly. In this problem, we were interested in exploring how well students could understand (and predict) the bandwidth behavior of a slightly modified circuit(Figure 2b) in comparison to an already known (Figure 2a). By cascoding the first stage, we minimize the Miller effect that multiplies the effective value of C1. Students experienced more difficulties in deriving the small-signal equivalent circuit (12% of the students). Some (15%) failed to apply steps 1–4 of the OCTC method. A number of students (12%) did not complete the solution or failed due to erroneous mathematical calculations (5%). Students who used the frequent form of Figure 1 solved the problems easier and ended up with the correct solution. Most of the students who did not use it was confused, found wrong solutions or did not complete the problem. The last ones were mainly students who missed some (or all) of the OCTC lectures or did not devote the necessary time to prepare (the same observation applies in the case of Problem 1).

3.2. Students' Performance—Sampling Test

In question 1, 59 students (about 72%) answered correctly. In question 2a, 55 students (about 70%) answered correctly. In question 2b, 47 students (about 57%) answered correctly that the limited amplifier bandwidth was mainly due to capacitor $C_{\mu 1}$. But only 29 students (about 35%) explained that this happens due to the Miller effect of the capacitor $C_{\mu 1}$. Question 2c was more difficult. In this question, we were interested in exploring if students could propose a circuit slightly modified with better behavior (smaller resistance, so smaller time constant and thus bigger upper cutoff frequency which means bigger bandwidth). Only 17 students (about 21%) answered correctly, that converting the first stage of the amplifier to cascode decreases the Miller effect, which "multiplies" the contribution of the capacitor $C_{\mu 1}$.

3.3. Students' Performance—Final Exam

Students' academic performance is one of the most widely used quality metrics when evaluating a course, a curriculum, a pedagogical approach or a learning preference [13]. The degree of achievement of the course objectives can be estimated from the number of students achieving a passing grade in the course exams. As the evaluation criteria are closely related to the measurement of the fulfillment of the course objectives, the higher the grades, the higher the degree of achievement. In order to estimate the impact of the course on the students' academic performance, an analysis of their grades in four exam tests (February and September of the first year, February and September of the following year) was conducted.

The final exam is held twice a year (usually in February and September) and is graded out of one hundred percent (100%). There is always a question that refers to OCTC and is graded with a maximum of 25%. The students are given a two or three-stage amplifier with BJTs or MOSFETs and are asked to find a simplified expression of the small signal's transfer function. This involves the calculation of low frequency gain $A\ f_{-3dB,OCTC}$. The students are led step by step to the final question, under smaller sub-questions that ask for the values of the parasitic capacitance resistors R_C.

The results presented here refer both to the OCTC question and the overall exam performance out of 100%. The numeric values of their grade distribution are shown in Tables 3 and 4 correspondingly and discussed in the next section. It is important to note here that the final exam questions' level of difficulty does not significantly change. In addition, the total number of students that registered for the course "Electronics III" was 143 for the first academic year and 158 for the following academic year. The number of students that took at least one of the two final exams per year was 105 and 120 correspondingly. The percentages shown are computed out of the number of students participated in each exam individually (51, 21, 63 and 11 correspondingly) and had taken the course for the first time.

Table 3. Open-circuit-time-constant (OCTC) question performance distribution (%) for students taking the final exam, from February of the first academic year to September of the second academic year

OCTC Grade (%)/Exam	Feb. Year 1	Sep. Year 1	Feb. Year 2	Sep. Year 2
85–100	21.6	4.8	27.0	45.4
70–84	15.7	14.3	38.1	18.2
55–69	13.7	19.1	17.4	18.2
40–54	15.7	19.1	7.9	18.2
<40	33.3	8.6	9.5	0.0
Mean OCTC grade	52.4	46.5	72.6	80.4

Table 4. Final exam student's performance distribution (%), from February of the first academic year to September of the second academic year.

Overall Exam Grade (%)/Exam	Feb. Year 1	Sep. Year 1	Feb. Year 2	Sep. Year 2
85–100	2.0	9.5	7.9	27.3
70–84	11.8	0.0	15.9	45.5
55–69	25.5	9.5	25.4	9.1
40–54	23.5	28.6	19.0	9.1
<40	37.2	52.4	31.7	9.1
Mean Exam grade	44.9	41.8	53.7	72.3

3.4. Quantitative Evaluation

Two anonymous surveys related to the students' perspective on the course were made, one at the beginning (pre-test) and the other at the end of the semester (post-test). The performance metrics that follow were used [12]. There is a link between the two surveys. The questions of the two quality surveys are the following.

Pre-test (first survey questions, at the beginning of the semester):

- Q[1.1] The course will increase my affinity to OCTC method.
- Q[1.2] I am interested in the course.
- Q[1.3] The effort imposed by the course is worthwhile because of the abilities and knowledge that I will acquire.
- Q[1.4] The use of simulation tools will increase my affinity to the OCTC method.
- Q[1.5] The use of simulation tools will help me to improve my academic results.

Post-test (second survey questions, at the end of the semester):

- Q[2.1] The course has increased my affinity to the OCTC method.
- Q[2.2] The course was interesting.
- Q[2.3] The effort imposed by the course was worthwhile because of the abilities and knowledge acquired.
- Q[2.4] The use of simulation tools increased my affinity to OCTC method
- Q[2.5] The use of simulation tools has helped me improve my academic results.

In this survey, a Linkert scale of 1–5 was used, which means that in order to answer the questions, the students had to choose between five answers. The rating scale is as follows: 5 = strongly agree, 4 = somewhat agree, 3 = neither agree nor disagree, 2 = somewhat disagree, 1 = strongly disagree. The results are shown in Tables 5 and 6 correspondingly.

Table 5. Pre-test results (first survey)—percentage (%) of answers per question

Rating/Question	Q[1.1]	Q[1.2]	Q[1.3]	Q[1.4]	Q[1.5]
1	13.9	18.0	22.9	9.0	8.3
2	24.3	16.7	27.8	18.7	8.3
3	38.2	31.2	23.6	29.9	25.7
4	15.3	28.5	20.1	25.0	27.1
5	8.3	5.6	5.6	17.4	30.6
Mean Rating Value	2.80	2.87	2.58	3.23	3.63

Table 6. Post-test results (second survey)—percentage (%) of answers per question.

Rating/Question	Q[2.1]	Q[2.2]	Q[2.3]	Q[2.4]	Q[2.5]
1	4.2	8.3	10.4	2.8	3.5
2	20.1	10.4	11.1	7.6	11.1
3	38.9	25.0	27.8	10.4	26.4
4	21.5	35.4	26.4	43.1	31.2
5	15.3	20.9	24.3	36.1	27.8
Mean Rating Value	3.24	3.50	3.43	4.02	3.69

4. Discussion

From the above results (Tables 5 and 6), it can be concluded that the majority of the students managed to correctly solve the problems. Students were able to predict which of the capacitances has the greatest impact on limiting the amplifier bandwidth. However, there were some students who were not able to overcome the difficulties. The wrong calculation of the resistance seen across the terminals of the capacitors was the main mistake of those who answered incorrectly. This was due to deriving an incorrect small-signal equivalent circuit initially, or incorrect equivalent circuit transformations during steps 1–4 of the OCTC method and wrong mathematical calculations at steps 5–6. Students who used the frequent form of Figure 1 solved the problems easier and ended up with the correct solution. Most of the students who did not use it were confused, arrived at the wrong solutions or did not complete the problem. The last ones were mainly students who missed some (or all) of the OCTC lectures or did not devote the necessary time to prepare.

The undergraduate students' performance on the homework tasks (the two examples described in Teaching Examples) shows that most of them spend a sufficient amount of time to understand the basic amplitude analysis principles, OCTC method, and its value. The sampling test given to them during the course verifies that about 70% have an understanding of how to use the analysis tools described in Section 2.2 in order to compute parasitic capacitance resistors fast. A smaller percentage has shown the ability to estimate which part of the amplifier circuit is responsible for the bandwidth reduction and how this could be optimized [7,9,14,15].

An observation at the final exam's performance during the last two years shows important improvement at both the OCTC and overall exam scores. The percentage of students that achieve more than 85% at the OCTC question has increased from 21.6% to 27% in the February exam and from 4.8% to 45.5% for the September exam. At the final exam grade, the corresponding increases were from 2% to 7.9% (February) and from 9.5% to 27.3% (September). Moreover, the percentage of failure has dramatically decreased whereas the average grades have improved by $20-30\%$ for the OCTC question and by 10% in the February final exam and even 30% in the September exam. This shows that the students have developed an increased ability in understanding and implementing fundamental amplifier analysis principles, including bandwidth detection, something that undoubtedly will assist them in the direction of analog integrated circuit design [15].

In the first survey, students' expectations and interest in the course were moderate at the beginning of the semester (questions Q[1.1], Q[1.2] and Q[1.3]). However, their answers in questions Q[1.4] and Q[1.5] reflected their positive attitude toward the use of simulations. In the second survey, students admitted that the course had increased their ability with the OCTC method (Q[2.1]) and they were interested in the course (Q[2.2]). Of great importance is the question Q[2.3], which roughly measures the ratio between two perceived variables, learning versus required effort. Students' answers indicated satisfaction with the course. The attitude of the students toward the use of simulations (Q[2.4] and Q[2.5]) was very positive. Finally, at the end of the second survey students were requested to make anonymous written comments (open question), if they wanted, about the teaching method and the learning process. From the 144 students, comments were made by 115 and most of them (63) stated that this teaching method should be applied again in the future for other students. This leads us to believe that the course matched the students' original expectations and that they were satisfied with the teaching method.

The teaching method for students is very important. The positive results gained from this study confirm the crucial role of the teacher in triggering the conceptual development of his/her students. In summary, the findings of the present study, support the conclusion that the OCTC method can be a valuable tool for teaching design concepts in electronics. This study suggests the kind of teaching materials which could be used and the way lesson plans could be designed in order to teach the OCTC method to undergraduate students as a tool for circuit analysis and amplifier design. It may also be used as a guide for implementing teaching ways for other subjects (eg., feedback, oscillators, noise, etc.) in electronics courses. In addition, this work provides a prospect for a future study not with an entire class, but with small groups of students too. It is worth noting that the present study focuses on the use of OCTC method in teaching, and therefore its findings should not be considered as a validation for an integral didactical intervention to the theories and subjects of electronics. In the latter case, to arrive at detailed conclusions would require a different research design and a didactical intervention which would last much longer.

5. Conclusions

The time constant method enables an easy approximate computation of the upper cutoff (-3dB) frequency of complex circuits. Introducing advanced undergraduate students to the OCTC method for the analysis and design of circuits assists them in understanding the usefulness of easy to apply methods in electronic circuits, even if it yields answers that might be approximate [7]. Simulators can then be used to provide final quantitative verification. The use of the simulator-based lab exercises, according to evaluation results, was beneficial to the students and improved their academic performance and their positive attitude towards the course [15]. The evaluation results of the course are very encouraging. The course has permitted students to acquire advanced knowledge and skills which will be beneficial in their later careers. The proposed teaching method can positively influence students' satisfaction, participation, initiative and improve their perception of basic concepts in circuit analysis and amplifiers' design. Our findings indicate that a combination of interactive lecture demonstrations, laboratory activities with simulations and in-class tutorials helps students to evaluate the role of an approximate calculation in relation to a simulation program for circuit analysis and design.

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Appendix A. Academic Year in Greece

Each academic year in Greece begins in the beginning of October and ends at the end of March. It is split in two semesters (spring and winter semester) with an exam period at the end of each semester and a supplementary exam period during August-September.

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