The Design of an Audio Power Amplifier as a Class Project for Undergraduate Students

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Abstract—**This paper presents the design of an audio power amplifier as a class project for undergraduate students of electrical engineering. This project is part of an electronics introduction class for undergraduate students and it has two main objectives: first to teach basic electronic circuit design concepts and second to motivate the students into choosing to learn more about analog circuit design. One of the main reasons for the creation of this project was the realization that most students considered analog design uninteresting. This project allows the students to design and build a circuit that actually has a practical application: at the end of the project the students can use the circuit that they designed to listen to music from an mp3 player through a loudspeaker.**

I. Introduction

In the first years of undergraduate program of electrical and computer engineering, the students have introduction courses to different areas (electronics, computer science, control systems, telecommunications, etc). In the last years of the program, the students have to choose which area they want to specialize by enrolling in more advanced courses from that area. This means that the introductory courses play an important role in shaping the preferences of the students regarding the different areas. Therefore, an introduction course in electronic design has to achieve two objectives: first to teach the students the relevant knowledge and second to motivate the students into wanting to learn more about electronic circuit design [1].

The introduction course to electronics has a bottom-up approach, from devices to circuits. First it starts by teaching how basic electronic devices (such as transistors and diodes) work, then it proceeds to teach basic circuits with only one transistor and finally to teach more complex circuits built using more than one transistor, including operational amplifiers. This course does not include the study of frequency response and stability of electronic circuits, because the students have not yet acquired the required knowledge about the Laplace and Fourier transforms. The course also includes laboratory classes, where the students experimentally test and measure various circuits, the laboratory classes conclude with the project that is described in this paper. The final project has to cover most of the subjects taught in the course allowing the students to consolidate the knowledge acquired in the course. At the same time, this project should motivate the students into wanting to learn more and be more interested in the design of electronic circuits. This project is carried out by groups of three students.

The paper is organized as follows. The next section describes the intended objectives of the final project. The circuit proposed for the project is described in section III and finally conclusions are drawn in section IV.

II. Objectives of the Project

The proposed design project has several objectives within the introductory course:

- Consolidation of the theoretical knowledge acquired in the course by the students.
- Improve the circuit design skills of the students
- Provide a “hands-on” hardware debugging experience to the students.
- Grade the students
- Motivate the students into wanting to learn more about analog electronic circuit design.

The first 4 objectives can be achieved by asking the students to analyze, design and build an electronic circuit with adequate complexity and then evaluating and grading their work. The circuit should include all the basic transistor circuits that were taught in the course. The circuit should be built without major difficulties or hurdles. Therefore the circuit should not be very sensitive to non-ideal effects, such as parasitic capacitances or inductances. Both the complexity of the circuit and the global difficulty of the project should be carefully adjusted in order to assure that the grades of the students are not too high or not too low. All these factors must be considered when selecting the circuit for the project.

In order to achieve the fifth objective, the circuit selected for the project should have a clear functionality and a practical propose, that the students can clearly perceive and relate to.

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This reasoning resulted in the selection of a power audio amplifier as the circuit selected for the project. This circuit can be used to amplify the output of an mp3 player and drive a load speaker; thus allowing the students to listen to music using a circuit designed and built by them. An audio amplifier also has the advantage of being a circuit with a low signal bandwidth which means that its behavior will not be significantly affected by parasitic capacitances present in the circuit assembly in the breadboard. Moreover, an audio amplifier can tolerate a THD of 1% and a bandwidth smaller than 20 kHz and still produce an acceptable sound quality.

The project has 3 phases. The first phase consists in the theoretical analysis of the amplifier circuit. The students are required to derive the expression for the operating point and small signal gain of the circuit. The second phase consists in the design of the circuit. Using the expressions derived in the first phase the students should design the circuit in order to achieve the desired performance goals. The design is confirmed through electrical simulations of the circuit. The third phase consists in building the circuit using a breadboard and testing the circuit in order to verify if it was correctly designed. This also includes testing the circuit using it to play music on a loudspeaker.

There are only 3 design goals set for the audio amplifier:

- The amplifier should be capable of delivering 0.5W to an 8 Ω load resistance.
- A DC open loop gain of at least 140.
- A DC closed loop gain between 9 and 10.

A schematic for the amplifier circuit is proposed to the students. The students are free (even encouraged) to suggest changes or improvements to this circuit. This means that there are many degrees of freedom in the design phase, which helps to stimulate the students into learning more about circuit design and it is also useful to grade the students, by helping to differentiating the best students, which typically tend to propose changes to the circuit.

III. PROPOSED AMPLIFIER CIRCUIT

The circuit of the proposed audio amplifier is depicted next in Figure 1.

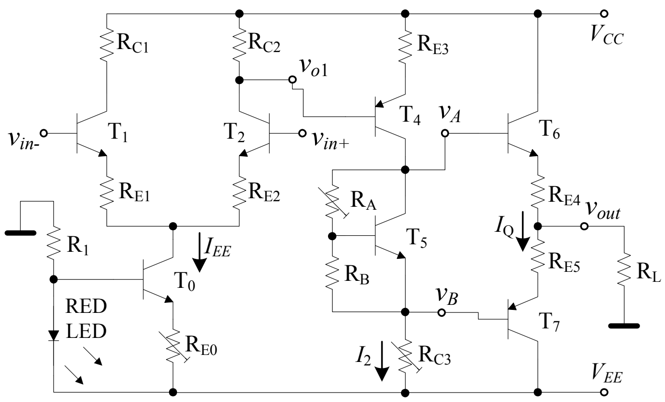

Figure 1. Schematic of the proposed amplifier (V_{CC}=5V, V_{EE}=-5V, R_{C1}=R_{C2}, R_{E1}=R_{E2}).

This circuit is a variation of a typical class AB power audio amplifier. The amplifier is composed by 3 stages. The first stage is a differential amplifier with emitter-degenerated transistors and resistive load (transistors T_1 and T_2). The current source of the differential pair is built using an emitter-degenerated transistor (T_0); the base voltage of this transistor is set by the ON voltage of a red LED, which is also used to signal when the circuit is ON. The second stage is PNP common emitter circuit (T_4); this stage is also the driver of the class AB push-pull output stage [3], which is composed by two emitter followers (T_6 and T_7). The value of the quiescent current of the output stage (I_Q) is determined by a V_{BE} multiplier circuit composed by T_5, R_B and R_A, this last resistor is an adjustable resistor in order to allow adjusting the value of I_Q. In an earlier version of the circuit resistors R_{E4} and R_{E5} did not exist and when the students adjusted the value of I_Q, sometimes this current would increase very rapidly due to thermal run away in transistors T_6 and T_7. The thermal run away occurs because transistors T_5, T_6 and T_7 do not share a heat sink and therefore have different temperatures. Since it is difficult to add a heat sink to the transistors in the bread board, the thermal run away speed is limited by adding the resistors R_{E4} and R_{E5} (with a value of 1 Ω), allowing enough time for the students to correct the I_Q value before the output transistors are destroyed. The maximum value for I_Q should be around 10 mA.

The circuit uses only bipolar transistors because this type of transistor is more robust than MOS transistors. Transistors T_1 to T_3 and T_5 are BC109, transistor T_4 is a BC179, transistor T_6 is a BD139 and transistor T_7 is a BD140. In an older version, the amplifier used MOS transistors in the differential pair. On many occasions, these transistors would stop working correctly. This was very problematic for the students, which could spend a lot of time trying to debug the circuit. From a learning point of view both transistor types (MOS and bipolar) have a similar behavior has small signal amplifiers, the only difference being the input impedance. It is important to mention that most of the general circuit analysis and design techniques that the students learn can be applied to both types of transistors.

The topology of the circuit was selected as a trade-off between the performance of the amplifier and the suitability of the project for maximizing the learning experience of the students. An example of this trade-off is the open loop gain of the circuit, which is smaller than the maximum possible gain of a two stage amplifier. This is to minimize instability and oscillation problems that can occur in the circuits built by the students. As such, the gain of the first and second stages is reduced through degeneration resistors. This is also important for the design process, since these resistors correspond to added degrees of freedom for the design space. The degeneration also improves the distortion of each stage, improving the audio quality of the amplifier. The number of transistors used in the circuit is small to simplify the assembly of the circuit in the breadboard. Some of the circuit modifications that can increase the performance of the amplifier are: using a current mirror as the load of the differential pair, replacing resistor R_{C3} by a current source similar to the one used in differential pair and finally replacing the output transistors by composed PNP-NPN transistors.

The amplifier is configured as a non-inverting amplifier, as shown next in Figure 2. The negative feedback allows reducing both the distortion and offset of the circuit, thus allowing the use of non-matched discrete transistors in the differential pair. The feedback factor is low (1/9) to reduce possible instabilities and unwanted oscillations in the circuit.

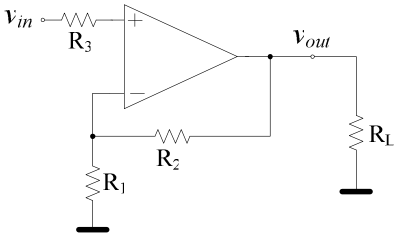

Figure 2. Schematic of the amplifier configured as a non-inverting amplifier

A. Circuit Analysis

The students' first task is the analysis of the circuit of the amplifier. This task consists in obtaining expressions that allow calculating all the DC voltages and currents in the circuit and calculating the small signal gain of the circuit as a function of the design parameters of the circuit.

Most of the DC voltages of the circuit are already defined (V_{out}=0V, $V_A \approx V_{BEon}$, $V_B \approx -V_{BEon}$, $V_{IN+}=V_{IN-}$=0V and all the V_{BE} voltages of the transistors), the remaining relevant voltages are a function of the bias currents (I_{EE} and I_2) and of resistors R_{C3}, R_{E3}, R_{C2} and R_{E2}. The number of independent parameters can be reduced from 6 to 4 by using Ohm's law to eliminate either I_2 or R_{C3} and by using the KVL in the loop that includes R_{C2} V_{BE4} and R_{E3}, thus eliminating either R_{C2} or R_{E2} or I_2. The students also have to determine the allowable voltage ranges in order to guaranty that all the transistors are in the active region. The voltage multiplier circuit and the differential current source are analyzed separately. In the first case the students have to determine suitable values for R_A and R_B in order that $1.8 \times V_{BEon} < V_A - V_B < 2.2 \times V_{BEon}$ for a given I_2 value. In the second case, the students have to obtain the value of R_{E0} in order to obtain a given I_{EE} value, assuming that the voltage across the LED is around 1.7V. After finishing the DC analysis of the circuit, the students have 4 variables available for the design of the circuit.

The open loop gain of the amplifier is obtained by analyzing the small signal equivalent circuit. This circuit allows to simplify the original circuit by replacing the differential current source by an open circuit and the voltage multiplier circuit by a short-circuit. Since the output stage works in class AB, it is necessary to consider 2 cases: the class A operation when both transistors are on and have a collector current equal to I_Q and the class B operation when only one transistor is on, with a collector current determined by the maximum amplitude over the load. The students should analyze both cases and find out the worst case in terms of stage gain and input impedance (the students assume that the NPN and PNP transistor have the same parameters). The expression for the gain of each stage of the circuit is obtained separately, taking into consideration the load effect of the following stage. By combining these separate gain expressions a global gain expression for the circuit is obtained. This expression is a function of a set of 4 variables selected from I_{EE}, I_2, R_{C3}, R_{E3}, R_{C2} and R_{E2}.

B. Design of the circuit

During the design phase of the project the students have to determine the values of all the resistances and currents in the circuit that are unknown in order for the circuit to comply with the project's goals. As it was explained before, the students have to determine the values of only 4 independent variables, because all the other circuit's parameters can be determined uniquely from these 4 variables. In order to simplify the problem, some further restrictions are suggested:

- The value of I_Q should be between 1 mA and 10 mA.
- The values of I_2 and I_{EE} and should be smaller than 20 mA
- The values of V_{BEon} for all transistors is 0.65 V
- The minimum value for R_{E2} and R_{E3} is 10 Ω.

The low impedance value of the load causes that the input impedance of the last two stages to be low. This is important because the students cannot ignore the loading effect of a stage on the previous stage. This results in more challenging design task for the students. During the design process the students learn about design trade-offs and optimal design points. For example if the value of R_{E3} is decreased while maintaining the value of I_2, the gain of the second stage increases, however its input impedance decreases, making the gain of the first stage smaller. This means that there is an optimal value of R_{E3} that maximizes the global gain of the amplifier. The students must navigate all the different trade-offs in order to obtain a good design for the circuit. In order to facilitate the design process, the students are encouraged to use a mathematical software tool (e. g. matlab) to plot the expression of the global gain of the circuit as a function of the different variables of the circuit, in order to better explore the design space of the circuit. At the end of the design process the students simulate the circuit using LTSpice [2] in order to verify if their design meets the project's goals. If necessary, a re-design is carried out, until the goals are met. At the end of this phase, the students show their project to a teacher that confirms the correctness of the design solution. The students are not allowed to build the circuit until the design is considered correct.

C. Assemby and experimental test of the circuit

Once the students finish the design phase they will build and test the amplifier circuit. The workbench available to the students is shown in Figure 3. And it consists of a dual power variable supply with current limiting, a function generator, a digital oscilloscope and a digital multimeter (not shown). Due to the large number of students enrolled in the course (over 100), the students have limited access to the laboratory, there is a weekly schedule (when a staff member is present) and only a limited number of students can be in the laboratory at a given time. The students have a total of 8 hours, over a 3 week period, to finish their project. This guaranty that all students have equal access to laboratory and it also makes the students more focused when they are in the laboratory. In previous years, there was open access to laboratory and it was frequent for students to spend a lot of time in the laboratory and most of that time was not productive. Moreover, sometimes the students would be stuck with a problem in the circuit that could be easily identified by a teacher present in the laboratory.

The students build the amplifier on a breadboard as shown in Figure 4. The students start by measuring the DC voltages of the first stage, then connect the second stage and verify that the voltages have approximately the expected value, (if necessary they use the adjustable resistors). Finally connect the output stage and the feedback circuit. After this, the amplifier is tested with sinewave signals and 1 kΩ load resistor; all the gains of the different stages are measured. If the circuit is working correctly, an 8 Ω load resistor is connected to the circuit, and all the different gains are measured again. When all the measurements are finished, the students connect a loudspeaker to the output of the amplifier and an mp3 player to the input, in order listen to music.

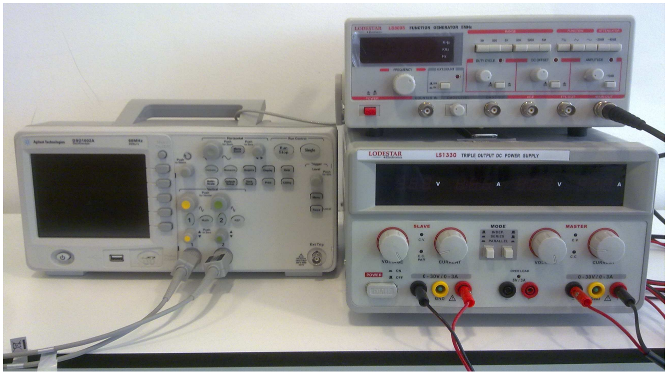

Figure 3. Laboratory workbench with test equipment

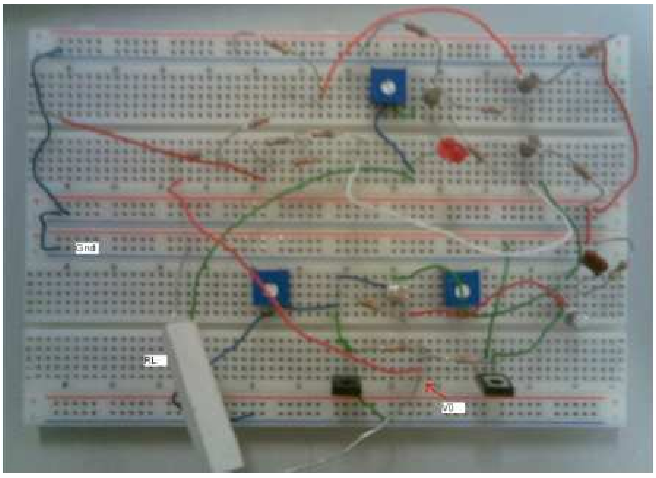

Figure 4. Photograph of an amplifier circuit buit by the students using a breadboard.

In approximately 30% of the circuits assembled by the students there are instability and oscillation problems, these can be easily solved by adding a 10 nF capacitor between the collector nodes of the differential pair. This problem is solved by the teachers present in the laboratory. This is actually a positive feature because the students learn that there are instability problems when using feedback and they are told that they will learn how to solve these problems in their next course about electronic design.

IV. Conclusions and Discussion of the Project Success

Observing the behavior of the students when they were in the laboratory, it was evident that most students were motivated by the proposed project. This was especially evident when a group of students finished their project, they would spend some time listening to music and in some cases the students would even record a video of the circuit and post it on social networks. We were also pleased to know that some students would also try to build a permanent version of the circuit (using PCB) for themselves.

The students are graded based on two evaluations, at the end of the design phase a teacher evaluates the design quality as well as if there are any differences between the efforts of each group element. After finishing building and testing the circuit, the students are once again evaluated by a teacher. The students also write a report on the project which is also evaluated. The final grade is obtained based on these evaluations. The students are graded using a scale between 0 and 20, a grade larger than 9 is considered positive. If a student concludes the first two phases of the project, he will receive a low positive grade. The distribution of the grades of the students is shown next in Figure 5.

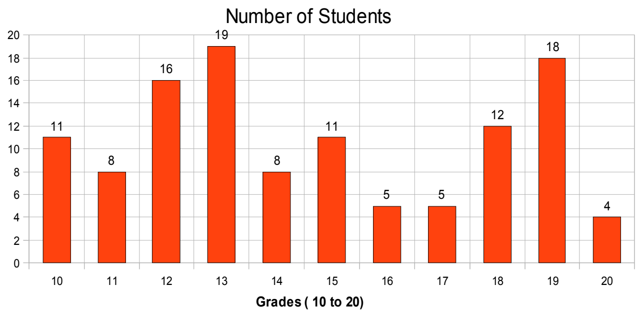

Figure 5. Distribution of the grades of the students.

The previous graph shows a shape with two clusters, one centered around 13 and the other around 18. This is a departure from the expected Gaussian shape for this graph. The second cluster corresponds to the students that excelled in the project. In our opinion, this is because these students were motivated by the project.

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