



DEPARTMENT OF ELECTRICAL AND
COMPUTER ENGINEERING

MAFALDA SOFIA VALENTE PENICHE
BSc in Electrical and Computer Engineering

DESIGN AND IMPLEMENTATION OF A HYBRID AUDIO PRE-AMPLIFIER WITH VACUUM TUBES AND TRANSISTORS

MASTER IN ELECTRICAL AND COMPUTER ENGINEERING
NOVA University Lisbon
September, 2024

DESIGN AND IMPLEMENTATION OF A HYBRID AUDIO PRE-AMPLIFIER WITH VACUUM TUBES AND TRANSISTORS

MAFALDA SOFIA VALENTE PENICHE

BSc in Electrical and Computer Engineering

Adviser: João Carlos da Palma Goes
Full Professor, NOVA University Lisbon

Examination Committee:

Chair: Paulo Miguel de Araújo Borges Montezuma de
Carvalho,
Associate Professor, NOVA University of Lisbon

Rapporteurs: Luís Augusto Bica Gomes de Oliveira,
Associate Professor (with Habilitation), NOVA University of Lisbon

Adviser: João Carlos da Palma Goes,
Full Professor, NOVA University of Lisbon

Design and Implementation of a hybrid audio pre-amplifier with vacuum tubes and transistors

Copyright © Mafalda Sofia Valente Peniche, NOVA School of Science and Technology, NOVA University Lisbon.

The NOVA School of Science and Technology and the NOVA University Lisbon have the right, perpetual and without geographical boundaries, to file and publish this dissertation through printed copies reproduced on paper or on digital form, or by any other means known or that may be invented, and to disseminate through scientific repositories and admit its copying and distribution for non-commercial, educational or research purposes, as long as credit is given to the author and editor.

This document was created with Microsoft Word text processor and the NOVAthesis Word template [40].

ACKNOWLEDGMENTS

I would like to take this opportunity to thank the brilliant accompaniment of my adviser João Carlos da Palma Goes. Thank you for guiding me in this project and encouraging me along every step of the way. Thank you for the availability and trust bestowed upon me all the way through. The amazing guidance that I had the pleasure to witness made sure that this project came as far as it did.

A special thanks to professor João Pedro Oliveira for guiding me and pushing me further with respect to the printed circuit board design. Your guidance was of the utmost importance in making sure that I can present this work with a working prototype. Thank you to Sr. Afonso Moutinho and Sr. Bruno Costa for sharing their vast knowledge and helping spark a bigger interest in making things by hand. Thanks to their help I could experience the joy of witnessing something you made with your hands work and for that many, many thanks to them.

I would like to express my gratitude towards the Electrotechnical and Computer Engineering Department for allowing and encouraging me to grow not only as a person but also academically. Thank you to all the professors and colleagues in the department with whom I made connections that will surely remain in the future. I would also like to thank the UN-INOVA Centre of Technology and Systems where I learned a lot about the complex work being developed in the electronics industry and where many resources were made available to aid in this work.

Thank you to my friends, some of whom I had the pleasure of accompanying these last five years. We went through a lot together and I could never thank you enough. Thank you to many others who I had the pleasure of being close to for a brief moment in time but had a great impact in making me the person I am today. Thank you to Matilde, José, Marcos, Afonso, with whom I have spent many great moments and can only hope that many more moments are surely yet to come. Lastly, thank you to my family, Mãe, Pai, Vasco, Bárbara, Milly, Duqui, Mel, Lola, Polga, Alvim, Nicki, Pepa, Balu for supporting me all these years and for always believing in me. These five years have led to moments of difficulty and self-doubt but you have inspired and helped me persevere.

“All flowers in time bend towards the sun.”
(Jeff Buckley and Elizabeth Fraser).

ABSTRACT

Vacuum tubes, commonly referred to as valves or tubes, were among the first components used in audio amplification circuits. However, the discovery of the transistor 75 years ago led to a significant decline in the use of vacuum tubes. Despite this, their unique sonic characteristics have proven difficult to replicate with solid-state technology. As a result, vacuum tubes remain highly regarded by audiophiles and continue to be relevant in audio circuitry, even amidst shortages.

Among engineers and audio enthusiasts, the debate regarding tube versus transistor sound prevails. Some claim to be able to hear the effect of the total harmonic distortion of overdriven valves and claim to be able to distinguish it from the overdriven transistor sound. Whilst the sound is different, it is known that many factors contribute to the overall design of audio equipment and it is acknowledged that both components, when employed in the appropriate contexts, can contribute significantly to the enhancement of a given design.

This work involves designing and implementing a hi-fi audio pre-amplifier with a hybrid configuration that incorporates both transistors and vacuum tubes, employing modern practices for noise reduction and cancellation.

The final pre-amplifier prototype made with printed circuit board achieves a gain of 21.3 dB. Additional performance parameters that were measured include frequency response and total harmonic distortion and noise. Using the ATS-2 Audio Precision it was observed that the final prototype exhibits low noise and distortion (1.2% on the left side of the pre-amplifier and 1.5% on the right side).

Keywords: pre-amplifier, vacuum tubes, transistors, hi-fi, hybrid, audio

RESUMO

As válvulas termiônicas foram dos primeiros componentes a serem utilizados em circuitos de áudio cuja função principal seria a amplificação do sinal. No entanto, a descoberta do transistor há 75 anos originou um período de declínio acentuado da utilização das válvulas. Apesar disso, as suas características sônicas únicas têm sido difíceis de replicar com recurso a transistores. As válvulas termiônicas mantêm então o seu prestígio e continuam a ser muito procuradas por comunidades audiófilas que sublinham a importância destes componentes em circuitos de áudio.

O debate sobre o som produzido por válvulas e transistor persiste entre engenheiros e comunidades entusiásticas do áudio. Muitos afirmam serem capazes de reconhecer e distinguir o som de válvulas saturadas da contraparte semicondutora, isto é, dos transistores. Os dois sons são de facto diferentes, contudo, reconhece-se que ambos os componentes, quando usados nos contextos apropriados, contribuem de forma significativa e positiva para melhorar a performance de um circuito de áudio.

Este trabalho propõe o projeto e a realização de um pré-amplificador de áudio híbrido, com recurso a transistores e válvulas na sua forma mais eficiente e utilizando as técnicas mais atuais de redução de ruído.

O protótipo final do pré-amplificador de áudio feito em placa de circuito impresso possui um ganho de 21,3 dB. Os aspetos de performance medidos foram a resposta em frequência e a distorção harmónica total e o ruído. Utilizando o dispositivo ATS-2 Audio Precision observou-se que o protótipo final possui um baixo ruído e distorção (1,2% no lado esquerdo do pré-amplificador e 1,5% no lado direito).

Palavras chave: pré-amplificador, válvulas termiônicas, transistores, hi-fi, híbrido, áudio

CONTENTS

1	INTRODUCTION	1
2	STATE OF THE ART	5
2.1	Vacuum Tubes: The Triode	6
2.1.1	Vacuum Tube Parameters	6
2.1.2	Vacuum Tube Characteristics	7
2.1.3	Vacuum Tube Topologies.....	9
2.1.4	Vacuum Tube Noise: Shot, Thermal and Flicker Noise	11
2.2	Junction Field Transistors	13
2.3	Bipolar Junction Transistors	15
2.4	Previous Works regarding noise-cancelling techniques	18
2.4.1	Wideband Balun LNA with Distortion and Noise Cancelling:.....	18
2.4.2	A low power balun LNA with Active Loads for Gain and Noise Figure Optimization:	20
2.4.3	Considerations about the mythic sound of tubes:	20
2.5	Main Objectives	21
3	THEORETICAL DEVELOPMENT OF THE PRE-AMPLIFIER	23
3.1	JFET Source Follower Topology	24
3.2	Noise Cancelling with Vacuum Tubes.....	27
3.3	Voltage Combiner Topology	35
3.4	Computer Simulations of the complete Pre-Amplifier: Final Performance Aspects	39
4	PRACTICAL DEVELOPMENT OF THE PRE-AMPLIFIER	43

4.1	Perforated Board Prototype.....	44
4.2	Printed Circuit Board Prototype	54
4.2.1	PCB Prototype Version 1	55
4.2.2	Results with ATS-2 Audio Precision.....	62
5	CONCLUSIONS AND FUTURE WORK PROPOSALS.....	67
5.1	Conclusions.....	68
5.2	Future Work Proposals	68

LIST OF FIGURES

Figure 2.1 - Load line analysis for $HT = 250\text{ V}$ and $R_a = 100\text{ k}\Omega$ (adapted from [11], [12]).	8
Figure 2.2 - Simple biasing technique for common cathode configuration.	10
Figure 2.3 - Simple biasing technique for common cathode configuration - cathode bias.	11
Figure 2.4 - Modeling the BJT as two diodes as to better understand its behavior.	16
Figure 3.1 - Simplified schematic of the proposed hybrid amplifier.	24
Figure 3.2 - Self Bias JFET input stage.	26
Figure 3.3 - Source follower implemented in <i>LTspice</i> program.	26
Figure 3.4 - Voltage gain of the source follower.	27
Figure 3.5 - Load line analysis performed for the ECC83/12AX7 valve [11], [12].	29
Figure 3.6 - Second stage of the pre-amplifier - noise cancelling topology.	30
Figure 3.7 - Noise cancelling topology: output.	31
Figure 3.8 - MATLAB script to generate thermal noise of vacuum tubes.	32
Figure 3.9 - Illustration of the PWF file format used to create the gaussian noise signal in the <i>LTspice</i> program.	32
Figure 3.10 - Circuit to test the partial noise and distortion cancelling.	33
Figure 3.11 - Output of both triodes with the noise contribution.	33
Figure 3.12 - Output of both triodes summed, in dark green.	34
Figure 3.13 - Voltage combiner topology.	35
Figure 3.14 - Voltage Combiner structure implemented in <i>LTspice</i> .	36
Figure 3.15 - Validating through simulations the voltage combiner structure for a 100 mV input signal.	37
Figure 3.16 - Voltage combiner behavior for a 500 mV peak-to-peak input signal.	37
Figure 3.17 - Final version of the voltage combiner.	38
Figure 3.18 - Hybrid hi-fi Audio pre-amplifier implemented in <i>LTspice</i> .	39
Figure 3.19 - Current mirror implemented in <i>LTspice</i> .	40
Figure 3.20 - Hi-fi audio pre-amplifier AC analysis.	41
Figure 3.21 - Circuit implemented for the noise cancelling topology in <i>LTspice</i> .	41

Figure 3.22 - Output of the pre-amplifier vs. ($V_{outcg} - V_{outcs}$).....	42
Figure 4.1 - Perforated board circuit.....	46
Figure 4.2 - Implementing and testing the first stage of the pre-amplifier.	46
Figure 4.3 - Results of the first stage the input signal, in blue, the output signal, in yellow...	47
Figure 4.4 – Output of the Grounded Grid with an input signal of 400 mV peak-to-peak and output signal of about 7.7 V peak-to-peak, supply voltage with 110 V.....	48
Figure 4.5 - Output of the Common Cathode with an input signal of 400 mV peak-to-peak and output signal of about 7.5 V peak-to-peak, supply voltage with 110 V.....	48
Figure 4.6 - ECC83 bottom view valve pinout (adapted from [12]).	49
Figure 4.7 - Voltage Combiner circuit implemented in the perforated board prototype.....	50
Figure 4.8 - Voltage combiner of the perforated board in <i>LTspice</i>	50
Figure 4.9 - Grounded grid output with all the stages connected between them and valves supplied with 48.6 V.	51
Figure 4.10 – Result obtained from the Grounded grid output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 2.64 V peak-to-peak.	51
Figure 4.11 - Common cathode output with all the stages connected between them and valves supplied with 48.6 V.	52
Figure 4.12 - Result obtained from the Common cathode output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 343 mV peak-to-peak.....	52
Figure 4.13 - Perforated board pre-amplifier prototype output with all the stages connected between them and valves supplied with 48.6 V.	53
Figure 4.14 - Result obtained from the perforated board pre-amplifier prototype output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 2.84 V peak-to-peak.....	53
Figure 4.15 - PCB prototype Version 1 Circuit.....	56
Figure 4.16 - Front view of the printed circuit board prototype Version 1 in <i>KiCad</i>	59
Figure 4.17 – Front 3D view of printed circuit board prototype Version 1 in <i>KiCad</i>	59
Figure 4.18 - Back 3D view of printed circuit board prototype Version 1 in <i>KiCad</i>	60
Figure 4.19 - Assembled hybrid hi-fi audio pre-amplifier PCB version 1.....	60
Figure 4.20 - Laboratory setup to test audio pre-amplifier PCB prototype version 1.	61
Figure 4.21 - Result of audio pre-amplifier PCB prototype version 1.....	62
Figure 4.22 - ATS-2 Audio Precision equipment.....	63
Figure 4.23 - Laboratory setup for measuring TDH+N and frequency response of the PCB prototype version 1 pre-amplifier.....	63
Figure 4.24 - Settings of ATS-2 for frequency response test.	64

Figure 4.25 - Result of the frequency response test with ATS-2 Audio Precision.....	65
Figure 4.26 - Settings of ATS-2 for distortion and noise (THD+N) test.....	65
Figure 4.27 - Result of the distortion and noise (THD+N) test with ATS-2 Audio Precision..	66

ACRONYMS

AC	Alternating Current
BJT	Bipolar Junction Transistor
BOM	Bill-of-Materials
CAD	Computer Aided Design
DC	Direct Current
JFET	Junction-Field Effect Transistor
MOSFET	Metal Oxide Field-Effect Transistor
PCB	Printed Circuit Board
SMD	Surface Mount Device
SNR	Signal-to-Noise Ratio
THD	Total Harmonic Distortion
THT	Through-Hole

INTRODUCTION

Vacuum tubes, commonly referred to as valves or tubes, were among the first components used in audio amplification circuits. However, the discovery of the transistor 75 years ago led to a significant decline in the use of these components. Nevertheless, their unique sonic characteristics have proven difficult to replicate with solid-state technology. The vacuum tube has enjoyed its niche in the audio field despite the rapid advances in solid-state devices. There are three areas where the sound of tubed equipment is preferred, namely: musical-instrument amplifiers such as guitar amplifiers, processing devices in professional recording studios and high-fidelity equipment in the audiophile market [1].

Audiophile communities and home audio enthusiasts are a group of individuals who are deeply interested in achieving high-quality performance from their audio equipment. Audiophiles demand a “pure” listening experience. To achieve this, the audio equipment should avoid introducing any artifacts such as a slight bass “boost” or treble “cut-off” within the human hearing range. These devices are designed to achieve very low noise and distortion as well as have a flat frequency response in the 20 Hz to 20 kHz range [2], [3], [4].

Among engineers and audio enthusiasts, the debate regarding tube versus transistor sound prevails and centers around the sonic differences between these two components. Some claim to be able to hear the effect of the total harmonic distortion of overdriven valves and claim to be able to distinguish it from the overdriven transistor sound. Selecting the appropriate engineering measurements to assess the performance of solid state or tubed audio equipment generates further controversy due to the inability to model the human auditory system accurately. Such measurements would allow for concrete statements regarding the sonic differences between both types of equipment and could help settle the debate among the different audio pre-amplifier designs.

Electrical engineers who design this equipment usually try to demonstrate that there is no difference between these two components by quoting specification sheets and electronic figures [2]. Musicians, however, tend to disagree with the previous statement. “Tube records

have more bass... The bass actually sounds an octave lower," [2]. Some musicians claim that the middle range of tube recordings is "very clear", even at low amplitude levels whilst transistor recordings usually emphasize the sibilants and cymbals [2]. "Transistor recordings are very clean, but they lack the 'air' of a good tube recording." "With tubes, there is a space between the instruments even when they play loud... transistors make a lot of buzzing" [2]. These are some of the perceived characteristics of valves and transistors by some musicians which show just how controversial this topic is.

We must yet mention that the music of the 1950s and '60s played an important role in shaping a cultural bias surrounding the mythical sound of valves. The distinctive distortions produced by vacuum-tube amplifiers became the standard "tone" for guitarists. This cultural phenomenon helps justify many musicians' preference for tubed equipment [2]. At this time, in the professional recording field, valve amplification was not only common but preferred.

Despite the debate, it is clear that there are advantages to using transistors in some instances and vacuum tubes in others. Some advantages of vacuum tubes include their high linearity, particularly in small-signal types, without relying on negative feedback. Transistors, on the other hand, need a considerable amount of negative feedback to achieve low distortion. The smooth clipping of vacuum tubes is often considered more musically pleasing than that of transistors which commonly exhibit sharp clipping. The sharp clipping of transistors occurs because of the extensive use of negative feedback [2].

Vacuum tubes exhibit tolerance to overloads and voltage spikes, and their characteristics remain highly independent of temperature, simplifying the biasing process. Transistor parameters, however, can vary considerably with temperature, leading to complications in biasing and an increased risk of thermal runaway. Transistors also have notable variations from unit to unit in crucial parameters such as intrinsic gain and threshold voltage.

Vacuum tubes have short operational lifetimes due to the depletion of cathode electron-emitting materials during operation. Their lifetimes range from 1 to 5 years for power tubes. Some advantages of transistors include their lower cost, especially in small signal circuits, and their smaller size compared to vacuum tubes. They can be easily integrated into a single die to create integrated circuits. Transistors have lower power consumption, particularly in small-signal circuits, and operate with low-voltage supplies. This ensures more safety and lower component cost. Vacuum tubes, however, require high operating voltages and consume a significant amount of power. They also dissipate a substantial amount of heat and have lower power efficiency [2].

The ongoing debate between tube and transistor sound remains unresolved, with opinions varying significantly depending on the perspectives of those consulted. Nevertheless, it is acknowledged that both components, when used in the appropriate contexts, can contribute significantly to improving a given design.

As a major reference for this work, we must mention some cherished vintage tube pre-amplifier designs, such as the Marantz Model 7 Preamp and the McIntosh C22. These models remain highly esteemed in the hi-fi audio community, having shaped the essence of what is considered a great hi-fi audio pre-amplifier. Another honorable mention is the Technics SU-V505 Class A pre-amplifier that I have at home. It has allowed me to experience my favorite records and serves as a great inspiration to create a design that can offer a similar experience upon the project's completion.

This work consists of designing and implementing an audio pre-amplifier with a hybrid configuration using both field-effect and bipolar junction transistors and vacuum tubes as well as employing modern practices for noise reduction and cancellation. The main motivation to work on such a topic comes from not having found projects where noise cancellation techniques have been performed using vacuum tubes. In this case, because we are developing an audio equipment, it is an interesting proposal to cancel noise, given that the audio pre-amplifiers must achieve low noise. The most common topologies were implemented and validated using transistors. However, and it being an audio application, this premise allows to experiment with components that thrive in this niche field whilst employing modern techniques to reduce noise which is, in turn, a crucial parameter in the audio world.

Regarding original contributions, we must highlight the use of three different kinds of devices, namely, the junction field transistor, the bipolar transistor and the vacuum tube. All these devices were deemed necessary to the design for distinctive reasons. The junction field transistor was used in the first stage of the pre-amplifier as a voltage buffer as it is known to be less noisy than their bipolar counterparts. It is very important to add the least amount of noise possible to the signal before valve amplification as, in the next stage, the input signal will be amplified significantly. The bipolar transistor was chosen to implement a current source and a voltage combiner due to its predictable characteristics, making it an ideal component for these parts of the design. The vacuum tube, as explained previously, is an obvious choice for this application as we intend to experiment with noise cancellation techniques on a three terminal device that was not yet used in this context. It makes sense to incorporate vacuum tubes in an audio application for it is highly regarded in this niche field as it has unique sonic characteristics.

To the best of the author's knowledge, this seems to be the first audio pre-amplifier based on a hybrid architecture, comprising vacuum tubes, field-effect and bipolar junction transistors employing advanced and modern noise-cancelling techniques. The complete system has been designed, simulated, prototyped in PCB (assembled), and experimentally evaluated relying on an ATS-2 Audio-Precision Lab equipment.

This work is organized as follows. In Chapter 2, we explore the devices that will be an integral part of the hi-fi audio pre-amplifier. As mentioned, this will be a hybrid design and

as such we will delve into the basic functions of vacuum tubes as well as junction field and bipolar junction transistors. Additionally, this chapter will feature some further considerations regarding power and how to properly set up these devices as the vacuum tube is a unique device in this regard. In Chapter 3, we introduce the design for the pre-amplifier and explain the theoretical approach as well as demonstrate the computer simulation results that were obtained and performance that was achieved for the hi-fi audio hybrid pre-amplifier. In Chapter 4, we go into further detail of all the practical work that went into the perforated board and PCB prototypes and discuss the differences in results from the theoretical and practical portions of this project. In Chapter 5, a summary of all the developed work will be featured as well as some recommendations for future work that can be done to improve this hybrid hi-fi audio pre-amplifier.

STATE OF THE ART

This work consists of designing and implementing an audio pre-amplifier with a hybrid configuration using transistors and vacuum tubes as well as employing modern practices for noise reduction and cancelation.

As mentioned earlier, among engineers and audio enthusiasts, the debate regarding tube versus transistor sound prevails. Despite the rapid advances in solid-state devices, vacuum tubes remain highly regarded in the audio industry for their distinct sound characteristics. This work acknowledges that both components, when employed in the appropriate contexts, can significantly enhance a given design.

This section will begin with a brief explanation of what an audio pre-amplifier is. The chosen design employs a hybrid configuration, combining both transistors and vacuum tubes. We will explore the key characteristics of vacuum tubes, particularly the triode, along with the basic operation of junction field-effect transistors (JFETs) and bipolar junction transistors (BJTs). Additionally, we will discuss common transistor topologies and how noise, including thermal and flicker noise, affects both triodes and transistors.

A pre-amplifier circuit is designed to amplify weak signals received from input sources with low amplitude. It increases the signal strength while minimizing additional noise and distortion, improving the overall signal-to-noise ratio. In audio applications, the pre-amplifier allows users to select signals from a variety of sources. Vintage pre-amplifiers typically feature inputs such as tape recorder inputs, phono (designed for turntables) and radio inputs [4], [5]. More modern designs, the common inputs are phono input and the equivalent to a tape recorder source but now usually referred to as auxiliary input, both designed to operate at line-level. Note that it is said they're equivalent because both inputs are designed to be line-level. Line-level, which refers to a standard signal strength for consumer electronics, is typically -10dBV.

The pre-amplifier must have an adequate input impedance and signal level handling capacity for the selected audio source. It should also be capable of adjusting the amplitude

and/or frequency characteristics of the input signal to achieve the desired tonal quality. Additionally, certain performance aspects need to be considered. These include Total Harmonic Distortion (THD), nominal gain, noise figure, input and output impedances, and bandwidth. Regarding specifications, the audio pre-amplifier should have a gain of about 10 V/V or 20 dB while achieving low noise and THD. The reference value for low noise and distortion (THD+N) should be between one and two percent (1 %- 2 %) [2], [3], [4].

This work focuses on hybrid topologies that integrate both transistors and vacuum tubes, employing modern practices for noise reduction and cancelation. The following subsections will address these components in detail.

2.1 Vacuum Tubes: The Triode

The thermionic valve was named by inventor, Sir Ambrose Fleming. This device allowed a unidirectional flow of current by controlling a flow of electrons which Fleming called 'thermions' [6].

Vacuum tubes typically consist of a cathode, grid, and anode, all enclosed in vacuum within a glass tube. There are several types of valves each differing on the number of electrodes. Diodes, for instance, are two terminal devices that are comprised of an anode and a cathode. The triode, which is most relevant to this work, is a three terminal device composed of a cathode, anode and grid. Other common types of vacuum tubes are the tetrode and pentode, with four and five terminals, respectively.

The cathode generates the electrons necessary for the device's operation, while the anode (or plate) attracts these electrons from the space charge when it is positively charged relative to the cathode [6]. The purpose of the grid is to control the flow of current.

When electrons are emitted from the cathode, they form a space charge—a cloud of electrons between the cathode and the grid [6], [7]. Introducing a negatively charged control grid moderates this space charge, allowing the grid to control electron flow and, consequently, the anode current.

The key advantage of vacuum tubes is their ability to control a significant anode current flow with a relatively small voltage applied to the grid. Since the grid voltage and anode current have a linear relationship, vacuum tubes can amplify weak signals with minimal distortion [6], [7].

2.1.1 Vacuum Tube Parameters

Before exploring the different topologies of valve amplification using the triode, it's essential to provide an overview of key valve parameters that play a crucial role in understanding

vacuum tube operation. Among these valve parameters the most crucial ones include the internal anode/plate resistance r_p , transconductance g_m , and the amplification factor, μ .

The internal anode/plate resistance r_p , refers to the resistance encountered by the alternating current between the cathode and the plate (anode). It is defined as the ratio of a small change in anode voltage divided by the corresponding change in anode current. Triodes typically have a relatively high value of internal resistance, in the order of 60-80 k Ω [8].

The transconductance g_m , describes the ratio of the change in plate current divided by change in the grid to cathode voltage (V_{gk}), given that other voltages remain constant. It is described in miliSiemens (mS) or sometimes seen in old datasheets described in micromhos (μ mhos). It can be calculated as the ratio of the amplification factor by the internal plate resistance, as shown in Equation 1 [8].

$$g_m = \mu / r_p \quad (2.1)$$

The amplification factor μ , defined as the ratio of a change in anode voltage to the corresponding change in control grid voltage in the opposing direction, provided that the plate current remains constant. The μ of a tube is useful for calculating stage gain [8].

In the upcoming sections, these parameters - g_m , μ , r_p - will be integral to understanding vacuum tube biasing and the valve amplification stage. Mastering these concepts is essential for the analysis presented in Chapter 3.

2.1.2 Vacuum Tube Characteristics

When designing a simple valve amplification stage, one of the fundamental techniques is load line analysis. This method is the foundation for properly biasing a vacuum tube and determining the quiescent point. This analysis describes a linear relationship between the high tension or high voltage supply to the anode and the anode resistor, R_a .

The first step in setting the quiescent point of the vacuum tube is to choose the high-tension supply voltage and the anode resistor value. Note that valves can and are usually used with a high-tension supply of 220 V or even 450 V. This can be observed in many pre-amplifier designs. Overall, let's assume a typical value of 250 V and a typical value of 100 k Ω for the anode resistor.

The anode resistor is in series with the valve. According to Ohm's law, if there is no current flowing through the valve then we know that there is no voltage drop across the resistor. We then have that the anode is at the same voltage than the power supply. This is one important point in this analysis. We have $I_a = 0$ mA and $V_a = 250$ V.

If the maximum amount of current can flow, then we can calculate how much this value would be again. Through Ohm's law, we simply divide the high-tension supply by the anode

resistor chosen and arrive at the maximum current that can flow in the anode of the vacuum tube for the given high voltage supply and anode resistor. We have $V_a = 250\text{ V}$ and $R_a = 100\text{ k}\Omega$, so the maximum current is $I_a = 2.5\text{ mA}$.

With the previous two points, we can design a load line where, for any given grid to cathode voltage potential, we know the value of anode current flowing. The plot that shows the anode current for various grid to cathode voltage, V_{gk} is referred to as the anode characteristics. The anode characteristics are one of the most useful set of curves on a vacuum tube datasheet as they show anode current I_a against anode voltage V_a , for different values of grid to cathode voltage, V_{gk} [9].

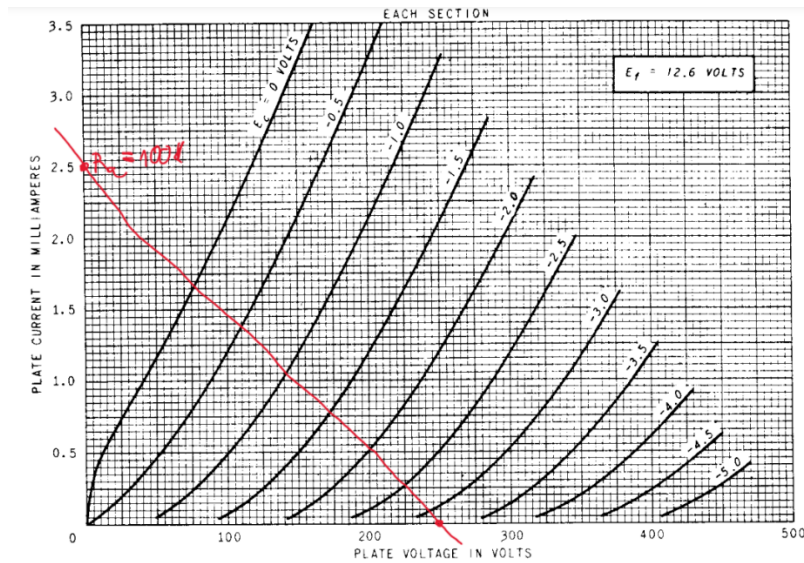


Figure 2.1 - Load line analysis for $HT = 250\text{ V}$ and $R_a = 100\text{ k}\Omega$ (adapted from [10], [11]).

The next step in designing the valve amplification stage is setting the grid to cathode voltage, V_{gk} . It is possible to observe that for lower V_{gk} values, the greater the current draw. However, as valves don't need a significant amount of current to amplify small signals, even at $V_{gk} = 0\text{ V}$, the anode current is about 1.7 mA .

Load line analysis is crucial as it highlights how vacuum tubes are voltage-controlled devices. For example, if the grid to cathode voltage, V_{gk} , is set at -2 V , the load line analysis shows that the anode current flowing would correspond to 0.5 mA with an anode voltage of 200 V . If the grid is raised to -1.5 V , then the anode current $I_a = 0.75\text{ mA}$ and the anode voltage $V_a = 180\text{ V}$. With a grid to cathode voltage swing of 0.5 V we can observe that at the anode, the swing corresponds to $200 - 180 = 20\text{ V}$ [7]. The voltage gain can be written in decibels (dB) and corresponds to:

$$A(\text{dB}) = 20 \log_{10} \left(\frac{V_{out}}{V_{in}} \right) \quad (2.2)$$

And so, we can calculate that 20 V swing divided by 0.5 V which corresponds to approximately 32 dB. This demonstrates how valves are effective at amplifying small signals.

From this analysis, we learned that valves operate at high voltages (typically a factor of ten greater than transistor circuits) and quite low currents. As shown in Figure 1, if there is no bias voltage ($V_{gk} = 0 \text{ V}$), then a large anode current flows. This is known as the space-charge limited condition and means that the flow of current is limited by the number of electrons that can be released from the cathode [12].

For optimal sound quality, the bias point is typically set near the middle of the grid curve since this allows the largest signal to be input without significant distortion (i.e., maximum headroom). This is usually the case for hi-fi, electro acoustic and jazz amps. The input stage of most amps is center biased, or nearly so. It must be remembered though, that the natural non-linearity of valves means there will always be a small amount of distortion. This characteristic is part of what makes valve amplifiers sound warmer and more textured than a solid-state amp [7].

This subsection has covered key vacuum tube characteristics namely the anode characteristics, present in valve datasheets. It also explains how to set the bias point for the valve to amplify a low amplitude small audio signal whilst minimizing total harmonic distortion (THD). The next subsection includes some more specific examples of valve amplification and introduce basic topologies, which will be used in following chapters.

2.1.3 Vacuum Tube Topologies

In this subsection, we will explore some basic vacuum tube topologies and create some basic valve amplification stages, one of the most common configurations being the common cathode configuration. Further topologies we will be looking at and performing the previous load line analysis are the common grid or grounded grid configuration.

Designing valve voltage amplifying stages is a relatively simple task when compared to more complex biasing options and techniques for solid-state circuit designs. To achieve proper biasing there are few options available to the designer. Additionally, vacuum tubes are very linear in their input/output transfer characteristics meaning that they require simpler circuit design. This improves the circuit performance and reduces further distortion [8].

Let's consider a grounded cathode triode voltage amplifier stage. Design choices include the type of grid bias system to use, and the type of anode load necessary to convert the changes in anode current, driven by changes in the control grid voltage, into a signal voltage output [8].

When it comes to biasing schemes, a few options are available. The simplest one consists of a large grid resistor that sets the grid potential as slightly negative in respect to the cathode, as shown in Figure 2.2. Using a $1\text{ M}\Omega$ resistor, the grid current that flows is in the order of magnitude of a few nanoampere, but it sets the grid at small negative voltage (of about 0.3 V). This biasing technique is simple to implement and provides the highest gain figure for a given anode resistor [8]. The low cathode impedance introduces very little noise. This will be particularly important not only because we're performing partial noise and distortion cancellation but because valve amplification is very significant and so, minimizing the noise will be crucial in this stage as we will see in Chapter 3.

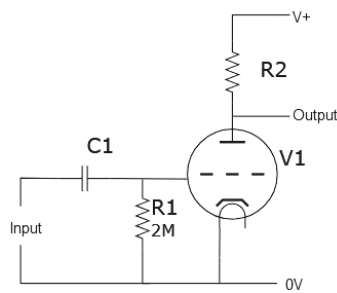


Figure 2.2 - Simple biasing technique for common cathode configuration.

Another commonly used biasing scheme is depicted in Figure 2.3. In this configuration, to set the grid to cathode voltage as negative, a resistor is included in the cathode so that the cathode voltage is made positive with regards to the grid. The addition of a bypass capacitor across this resistor is necessary so that the gain of the stage is not reduced.

A disadvantage of using this scheme when compared with fixed bias schemes is that the voltage present in the cathode circuit is effectively subtracted from the anode supply voltage which reduces the maximum possible undistorted anode voltage swing. This limitation can impact the overall performance of the amplifier stage, particularly in achieving high output without introducing distortion [8].

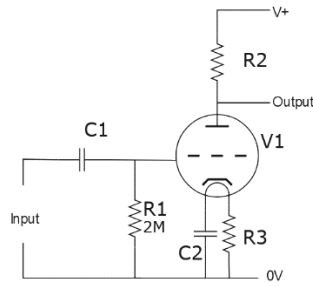


Figure 2.3 - Simple biasing technique for common cathode configuration - cathode bias.

There is an additional biasing scheme for vacuum tubes, but it is typically used in power output stages with directly heated tubes, which is not relevant in the case of the ECC83/12AX7 triode used in this project. Consequently, it isn't particularly applicable to pre-amplifiers. As such, these are the most common biasing schemes for vacuum tubes and are going to be used in the following chapters.

Regarding valve amplification schemes, the ones used in this work correspond to the common cathode and the common grid topologies. For noise cancellation, an inverting topology with negative gain is required, making the common cathode ideal for this purpose. The grounded grid is a simple voltage buffer with low input impedance and high output impedance and non-inverting topology which is what we need to perform the noise cancellation, as will be explored in later chapters. This introduction serves to clarify the design choices made, providing insight into how each topology contributes to the overall design.

2.1.4 Vacuum Tube Noise: Shot, Thermal and Flicker Noise

Reducing noise is crucial in audio circuitry. When describing noise, we are referring to the random noise generated by both passive devices such as resistors as well as active devices such as transistors and thermionic valves. The following subsections will focus on how noise manifests specifically in junction field-effect transistors (JFETs) and bipolar junction transistor (BJTs).

White noise has equal power in equal absolute bandwidth, i.e. with the bandwidth measured in Hz. Thus, there is the same power between 100 and 200 Hz as there is between 1100 and 1200 Hz. White noise is then characterized by a uniform distribution in the frequency domain and a Gaussian distribution in the time domain [15], [16].

There are two more significant noise mechanisms that affect thermionic valves which are Johnson noise and shot noise, which are both are forms of white noise. Both have Gaussian

probability density functions. These two basic mechanisms generate the noise in vacuum tubes as well as in both bipolar junction transistors (BJTs) and field-effect transistors (FETs), though in rather different ways [15], [17].

The noise originating from the thermionic valve is not completely understood and cannot be calculated accurately however, it is known that it originates from:

1. thermal agitation in the internal plate resistance of the tube;
2. shot effect and flicker effect from space current in the presence of space charge;
3. shot effect from electrons produced by collision ionization and secondary emission;
4. space charge fluctuations due to positive ions.

We won't be delving into the last two noise contributions listed as they're not significant contributions when compared to the first two in the scope of this work. Whilst the goal is to perform partial noise cancelation, we can consider that achieving the cancelation of the contributions of the thermal and shot noise are more than sufficient to validate the design. Nonetheless, all four remain potential sources of noise in thermionic valves.

The resistance component of the impedance between plate and cathode, i.e. the parallel of the internal resistance r_p , and the load impedance, is a source of thermal noise [18]. Since thermal noise arises from resistive elements, we can conclude, therefore that at least some portion of thermal noise will inevitably be present in the design [19]. Even with noise-reduction techniques, the resistive properties of these components ensure that thermal noise cannot be completely eliminated, and a portion will persist throughout the circuit.

$$\overline{V^2} = 4kT_0(r_p/\mu^2) [T_f/(T_0r_p) + 1/r_0]F. \quad (2.3)$$

Equation (2.3) gives the minimum thermal noise (in power) contribution of a thermionic, assuming all other noise sources are eliminated. It shows that reducing the temperature of the cathode, can effectively reduce the thermal noise generated. Additionally, the thermal noise contribution can be further reduced by increasing the value of plate resistance or of the amplification factor, μ .

Regarding, shot noise caused by the shot effect and flicker effect in the presence of space charge, Equation (2.4) describes the contribution of shot effect in the presence of the space charge present in the anode of the vacuum tube.

$$\overline{V^2} = 2ej(\partial i/\partial j)^2 (r_p/\mu)^2 F. \quad (2.4)$$

The previous equation demonstrates that shot noise at the input can be reduced by increasing the cathode temperature and by increasing the ratio of the amplification factor, μ , by the internal plate resistance, r_p , which is the definition of the transconductance, g_m , of the tube. It's important to note that the shot noise contribution is not affected by the load resistance.

Additionally, we must consider the contribution of flicker noise in the vacuum tube. When changes in electron emission occur over small areas of the cathode, it produces additional fluctuations, known as flicker effect. We can conclude that when in the presence of a complete space charge condition, the flicker effect voltage decreases [19], [20].

To conclude this subsection, we have examined the primary noise sources in a thermionic valve. We identified shot noise and thermal noise as the most significant contributors to noise in these devices, with shot noise being an inevitable presence. This work incorporates a well-established common gate and common source structure using thermionic valves to achieve partial noise and distortion cancelation of both noise and distortion. This approach is key to enhancing overall performance and sound quality in the hybrid pre-amplifier design.

2.2 Junction Field Transistors

The junction field transistor (JFET) is one of the simplest types of field-effect transistors. It is a three terminal device composed of the gate, source and drain. While these terminals share the same names as those in metal oxide semiconductor field-effect transistors (MOSFETs), they function differently. JFETs are used in many applications as amplifiers, switches, constant current- sources, mixers [21].

Junction field effect transistors are exclusively voltage-controlled meaning they do not require a biasing current, unlike bipolar junction transistors (BJTs). JFETs are a type of depletion mode transistor, meaning they conduct when there is zero voltage between its gate and source terminals.

In the presence of a reverse potential across the gate and source terminals, the depletion zone width is increased on either side of the junction. If the source voltage is increased, with respect to the gate voltage, the two depletion zones move closer together until eventually reach the “pinch-off” region characterized by very little current flow through the channel [8].

JFETs are also characterized by having highly variable V_g values that can be dealt with by implementing current-source biasing, but the low gain, which means low feedback and poor linearity, remains a problem. FETs have their uses when high input impedances and low noise are required [17].

Some popular biasing arrangements include the self-bias configuration where we get the gate-source voltage, V_{gs} , at a negative potential compared to the drain voltage by introducing source degeneration. This degeneration corresponds to having a resistor across the source to

create a voltage drop across the source at a higher potential than the gate terminal. Another common biasing technique consists of the voltage divider where, for a given resistor value chosen, we obtain the quiescent point and then adjust the voltage divider to set the negative potential of the gate voltage, V_g .

In the context of a hi-fi hybrid audio pre-amplifier design, understanding the noise characteristics of JFETs is critical, as noise levels can directly impact the overall sound quality. Further sections will analyze these noise contributions and their role in the pre-amplifier design.

Noise in JFETs

Regarding noise, JFETs exhibit different characteristics compared to bipolar junction transistors (BJTs), with noise primarily originating from the Johnson (or thermal) noise produced by the channel resistance [17]. This channel resistance is the inverse of the JFET's transconductance (g_m), indicating a strong relationship between noise and the selected operating (or quiescent) point chosen.

An approximate but widely accepted equation for describing the thermal noise density, e_n , is Equation (2.5) where k is Boltzmann's constant (1.380662×10^{-23}) and T is absolute temperature ($^{\circ}\text{K}$).

$$e_n = \sqrt{4kT \frac{2}{3g_m}} \text{ (in V}/\sqrt{\text{Hz}}; \text{ usually nV}/\sqrt{\text{Hz}}) \quad (2.5)$$

The JFET device can operate in three different regions: linear, active region and cut-off region. In the active (or saturation) region the behavior of the drain current (I_d) can be described by Equation (2.6).

$$I_{DS} = \frac{I_{DSS}}{V_{GS}^2(off)} [V_{GS} - V_{GS}(off)]^2 = I_{DSS} \left[1 - \frac{V_{GS}}{V_{GS}(off)} \right]^2 \quad (2.6)$$

The transconductance (g_m) is the ratio of change in drain current (I_d) by the change in the gate to source voltage (V_{gs}). From the fundamental equations describing the behavior of the drain current in the active region of operation of the JFET, we know that it's transconductance is proportional to the square root of the drain current, I_d . From Equation (2.5) we observe that the transconductance is again square rooted, meaning that the voltage noise is proportional to the fourth root of drain current (I_d).

As for current noise, a significant source in a JFET is the shot noise generated by gate leakage current. Usually, the gate leakage current is extremely low, which in turn means that

the current noise is very low. This is why JFETs have good noise performance with high source resistances. Note that the gate leakage current increases with the temperature. With an increase of 10 °C, the gate leakage current doubles and so we can conclude that there are instances where the JFET can be extremely noisy.

Overall, the JFET is a much quieter device when compared to the BJT except when they are exposed to high temperatures and have low source impedances which can make it, so their current noise is greater than that of the bipolar junction transistor [17]. This analysis of JFET behavior provides context for the design considerations explored in the following chapters.

2.3 Bipolar Junction Transistors

The bipolar junction transistor (BJT) is a fundamental component in modern electronics. Transistors have replaced the vacuum tube in many applications since the 1970's. The bipolar junction transistor is a device with three terminals: base, collector and emitter. It can be one of two types: NPN or PNP, which differ in their material composition but serve the same functional purpose.

BJTs offer several advantages, such as high transconductance and predictable operation, making them more versatile compared to FETs [17]. It is essential to understand that the BJT is current-controlled device due to the linear relationship between the base current I_b and the collector current I_c . By adjusting the voltage across the base and emitter terminals as well as the emitter and collector terminals, the region of operation of the device changes. Key parameters of BJTs include the current gain, also referred to as β (or h_{fe}). It corresponds to the ratio of base current, I_b by the collector current I_c . The value of β drastically changes with temperature, with the value of collector current, it varies even from unit-to-unit for the same transistor type.

The NPN type bipolar transistor can be modeled by two diodes as can be seen in Figure 2.4.

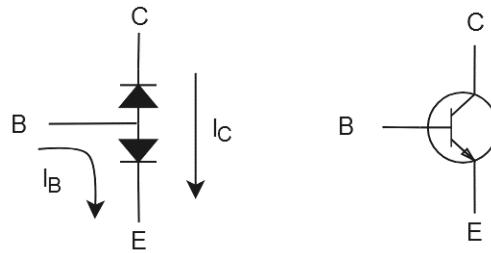


Figure 2.4 - Modeling the BJT as two diodes as to better understand its behavior.

Understanding the basic model of a bipolar junction transistor (BJT) is crucial to grasp its operation. When the base is an open circuit, no collector current flows, as the base-collector junction behaves like a reverse-biased diode. In contrast, the base-emitter junction is forward-biased, meaning the transistor turns on only when the base-emitter voltage (V_{BE}) is sufficiently positive. Generally, V_{BE} must be at least 600 mV for the transistor to turn on, though most literature assumes it is fully on when $V_{BE} > 0.7$ V.

Two common biasing schemes are the fixed bias and voltage divider configurations, both of which aim to set the base-emitter voltage (V_{BE}) above 0.7 V. The fixed bias method will be used in the design and is further explained in Chapter 3.

Once the base-emitter junction is forward biased, the next step is to establish the correct collector current. The emitter current is the sum of the collector current (I_C) and the base current (I_B), with I_B being a function of I_C and the transistor's current gain (β or h_{fe}) value.

According to the biasing arrangement chosen, the way in which the collector current can be set differs. Choosing the appropriate DC operating point consists of setting the base-emitter voltage with a voltage across greater than 0.7 V and choosing the appropriate value for the collector current. The next step is then to perform the small signal analysis and obtain the values for input and output impedance as well as for the gain of the stage.

This overview provides a basic understanding of how BJTs function and what considerations are necessary when using them, particularly in the hybrid hi-fi audio pre-amplifier design further described in Chapter 3. The final step in understanding BJT's has to do with understanding how their contribution in terms of noise.

Noise in Bipolar Junction Transistors

This subsection will cover how thermal (Johnson) noise manifests in the bipolar junction transistor (BJT). Two key transistor parameters for understanding noise are the base spreading resistance, r_{bb} , and the intrinsic emitter resistance, r_e . This last resistance, r_e , is an expression of the V_{BE}/I_C slope and therefore should be noted that it is not a physical resistance [17].

In noise analysis, a BJT can be modeled as a noiseless transistor with two theoretical noise sources: a theoretical noise voltage source in series with the base, to describe 'voltage noise' and a theoretical noise current source connected from base to emitter, to described 'current noise' [17].

Bipolar Transistor Voltage Noise Density

The voltage noise, v_n , in bipolar transistors has two components that arise from the parameters that were just mentioned. The first component corresponds to the Johnson (or thermal) noise generated in the base spreading resistance, r_{bb} and the second component refers to the collector current shot noise which creates a noise voltage across the intrinsic emitter resistance, r_e .

Regarding the thermal noise, running BJTs at lower temperatures can significantly improve the noise contribution, i.e. the lower the operating temperature, the lower the noise generated. The shot noise decreases as the collector current (I_C) increases. Note that the shot noise increases with the square root of the collector current and so, the total voltage noise density, v_n , falls but it falls slowly as the collector current I_C , increases.

$$v_n = \sqrt{4kTr_{bb} + 2(kT)^2/(qI_C)} \text{ (in V}/\sqrt{\text{Hz}}; \text{ usually nV}/\sqrt{\text{Hz}}) \quad (2.7)$$

There is an extra voltage noise source which arises as flicker (or 1/f) noise produced by the base current flowing through the base spreading resistance, r_{bb} . This contribution is only significant at high collector current values and affects the signal in low frequencies. We will disregard this noise contribution due to not being that relevant when compared to thermal and shot noise [17].

Bipolar Transistor Current Noise Density

Current noise in BJTs is primarily caused by the shot noise of the base current I_B flowing through the base of the transistor. This current noise increases with the square root of the base current, I_B .

As previously noted, the base current is the ratio of collector current and the current gain (β or h_{fe}) and so if the collector current increases, the base current also increases although non-linearly. So, for a fixed collector current, you get less current noise with high-beta transistors because there is less base current. In Equation (2.8) the current noise density is expressed in $\text{A}/\sqrt{\text{Hz}}$ where q corresponds to the charge of an electron and I_B is the base current of the transistor.

$$i_n = \sqrt{2qI_B} \text{ (in A}/\sqrt{\text{Hz}}; \text{ usually pA)} \quad (2.8)$$

It's important to note that the presence of both current noise and voltage noise means that transistor noise cannot be minimized by simply increasing the collector current to its maximum. While increasing the base current I_B reduces voltage noise, it simultaneously increases current noise [17].

We can then observe that there is a trade-off between both noises and the way they affect bipolar transistors. This concludes the introduction of the bipolar junction transistor, which will be primarily used to perform single ended to differential signal conversion in this work.

2.4 Previous Works regarding noise-cancelling techniques

This work consists of designing and implementing an audio pre-amplifier with a hybrid configuration using both field-effect and bipolar junction transistors as well as vacuum tubes and employing modern practices for noise reduction and cancellation.

In this subsection, we will review previous research that aligns with the objectives of the pre-amplifier being developed. Firstly, given the interest of this work in the use of modern techniques to reduce noise in vacuum tubes, we will explore noise-cancelling techniques in radio-frequency (RF) CMOS amplifiers namely, the CG-CS topology which will be implemented in the pre-amplifier and discussed in later chapters. Additionally, we will examine a similar project that focuses on a vacuum tube pre-amplifier, where various design measurements were conducted.

This review aims to provide clarity on the proposed work while highlighting key previous research that directly contributes to the development of a hybrid hi-fi audio pre-amplifier using both vacuum tubes and transistors.

2.4.1 Wideband Balun LNA with Distortion and Noise Cancelling:

The noise cancelling stage is achieved by the combination of a common-gate (CG) stage and a common-source (CS) stage. This is a well-known structure which has been first found in the literature about 15 (fifteen) years ago [22], [23]. The traditional way of implementing this structure states that the devices should have identical size and bias for the CG and CS stages [24]. This structure allows for a low NF (noise figure), since the thermal noise of the device M1 (common gate structure) is cancelled out. The noise produced by the device in the CG configuration appears in phase at the two outputs terminals, while their signals are in opposition. Thus, it is possible to obtain double the gain and cancel its noise.

Note that, there are structures that can reduce a larger portion of the noise generated by the components present in the design, however, those structures offer only a narrow band. With this structure a noise cancelation over a wide band is possible to achieve with a sub 3dB NF (noise figure). Electronic devices for audio applications have what is considered a wide band that ranges with frequencies from 20 to 20 kHz, the human hearing range.

In [23], the previous structure is subject of 3 (three) different approaches in terms of biasing to analyze the trade-offs in terms of noise and distortion canceling as well as gain, that is possible to achieve for 3 (three) different design options as follows:

1. the transconductances of both CS and CG devices and their respective load resistors are equal. This corresponds to the traditional way of implementation of this structure and means that: $g_{mCS} = g_{mCG}$ and $R_{CS} = R_{CG}$.

2. The transconductance of the CS transistor is n times superior to the transconductances of the CG transistor and their respective load resistors are equal. This means that: $g_{mCS} = n \cdot g_{mCG}$ and $R_{CS} = R_{CG}$.

3. The transconductance of the CS transistor is n times superior to the transconductances of the CG transistor and CS load resistor is n times smaller than the CG load resistor. This means that: $g_{mCS} = n \cdot g_{mCG}$ and $R_{CS} = R_{CG}/n$.

In [23], for the 3 design options their gain, gain imbalance and noise figure are evaluated and it is found that for the third design option, the NF (dB) is the lowest, the gain is constant and reaches about 18 dB whilst the output gain imbalance corresponds to 0 dB in RF applications. The output gain imbalance corresponds to the ratio of voltage gain of the CS and the CG stage. We know that the gain required in the CS-stage to cancel the distortion products of the CG-device equals the gain required to obtain output balancing leading to the conclusion that simultaneous balancing and cancellation of unwanted noise and distortion currents of the CG transistor is possible.

In this work, we chose to use the suggested topology in [23] but using different devices such as thermionic valves. The design option that was chosen was the traditional approach where the transconductances of both devices and anode resistors, in the case of the thermionic valves, have equal values. Furthermore, being an audio application, reducing noise is important and using vacuum tubes which are highly regarded in this niche field is an interesting combination that should impact the pre-amplifier design positively. Note that some challenges that might arise come from the different noise profile of MOSFET (metal oxide semiconductor field-effect transistors) and vacuum tubes. Noise generated from these devices behave differently.

2.4.2 A low power balun LNA with Active Loads for Gain and Noise Figure Optimization:

This work is relevant as it utilizes the noise cancelation architecture that we will be using. Note however, that the active loads approach present in this work is more relevant in radio-frequency (RF) applications. This work shows an improvement in the design by substituting the passive loads present on the drain of both common-gate (CG) and common-source (CS) devices by active loads, i.e., MOSFETs with their respective drain and gates shunted therefore behaving as linear voltage-controlled current sources, i.e., the same behavior as a simple resistor.

In [24], a balun low noise amplifier with noise and distortion canceling with active loads is proposed. The main objective is achieving an architecture characterized for its low-cost, low area and low power. The balun LNA is implemented using 130 nm CMOS technology. The LNA has a noise and distortion canceling architecture, that consists of the common-gate (CG) and common-source (CS) stages. This architecture aims to boost the gain and reduce the noise figure (NF) of the conventional LNA.

Two circuit prototypes were designed in 130 nm CMOS technology to make a direct comparison between the conventional design with the passive loads, i.e. resistors, with the proposed design using active loads. By using active loads instead of passive loads such as resistors, the architecture should allow a supply voltage reduction, leading to lower power consumption and the architecture should also allow for a reduction of the circuit die area. Regarding the LNA implementation in a 130 nm CMOS technology results, a comparison is conducted to illustrate the performance of the LNA with passive versus active loads. Both circuits have the same test circuit and power consumption. The LNA with active loads has obtained a gain improvement of about 3 dB and a NF reduction of about 0.5 dB.

2.4.3 Considerations about the mythic sound of tubes:

In [25], the paper attempts to verify how a metrological approach can help provide an objective opinion about vacuum-tube sound. The findings indicate that the distortion produced by vacuum tubes is often perceived as more pleasant due to the predominance of even-order harmonics. The focus of [25] is pre-amplifiers using valves, akin to the proposed work hence its relevance.

One of the key concepts discussed in [25] is harmonic distortion, which has been covered in previous chapters. Harmonic distortion corresponds to the sum of the powers of all harmonic components relative to the power of the fundamental frequency. In electronic circuits,

harmonic distortion increases as an effect of non-linearity of devices, such as the thermionic valve.

The paper also addresses how distortion is perceived both visually and audibly. Interestingly, it notes that a loudspeaker with 5 % Total Harmonic Distortion (THD) and fewer high-order harmonics tends to sound better than a loudspeaker with only 2 % THD but with more high-order harmonics [25]. The most efficient technique to objectively evaluate harmonic distortion is spectral analysis.

Two primary types of distortion are highlighted: crossover distortion, which affects low-level signals, and clipping distortion, which occurs at high levels. In [25], it is observed that crossover distortion shows no significant difference between tubes and transistors, contrary to clipping. Note that both distortions occur due to different electrical phenomena in the pre-amplifier.

In [25], a test is made on 20 identical valves, to measure the dispersion of parameters such as g_m , r_p , and μ which correspond to transconductance, internal resistance, and amplification factor of a vacuum-tube. The valve used was the EF 80 pentode. It is observed that the batch of tubes has a considerable dispersion of transconductance. Furthermore, the valves seemed to not be totally stable over time although results are consistent with manufacturer tolerances.

The paper concludes that comparing audio reproduction devices between them, scientifically, seems to be unproductive. It was found that technical criteria alone are insufficient to determine superiority. Ultimately, listening preferences, a subjective parameter, are the most determining criterion. It seems unavoidable that the final decision belongs to the listener.

The conclusion of this paper aligns with the author's opinion on the subject. I find it important to look at this problem from a "big picture" perspective. Audio reproduction devices exist in a chain of diverse equipment. That is, in an audiophile's home, we might find a vacuum tube pre-amplifier with certain specifications and following it a solid-state power amplifier, a device that is responsible for driving the output signal to the speakers, which are low impedance devices (4 Ohm or 8 Ohm). Objectively, it is very difficult to evaluate and distinguish the audio contributions of the devices separately. All this proves that, inevitably, the best audio reproduction device differs with the listener himself.

2.5 Main Objectives

In this section, we will cover the main objectives of this work. The proposed work consists of designing and implementing a hi-fi audio pre-amplifier with a hybrid configuration using transistors and vacuum tubes utilizing modern practices for noise reduction and cancelation.

Building upon the insights gained from earlier subsections, we've explored the behavior of these components and their susceptibility to noise, specifically thermal and shot noise. In this section, the aim is to delve deeper into the utilization of both components and revisit certain aspects discussed in the introduction.

We know that the smooth clipping of vacuum tubes is considered more musically pleasing than that of transistors which exhibit sharp clipping [1]. Many individuals, namely, audiophiles find pleasure in the amplified sound produced by vacuum tubes. People also appreciate the total harmonic distortion (THD) of vacuum tubes but not necessarily the lower signal-to-noise ratio (SNR). We aim to achieve the best of two worlds: the pleasant THD from the vacuum tubes with improved SNR.

The pre-amplifier circuit design is based on the combination of transistors (BJTs and JFETs) and thermionic valves employing advanced noise-cancelling techniques (by properly combining the equivalent "common-gate" and "common-source" topologies and relying on 2 triodes), as previously stated. Furthermore, we haven't found projects where noise cancellation techniques have been performed using vacuum tubes. The most common topologies were implemented and validated using transistors. Within the audio world, this premise allows to experiment with components that thrive in this niche field whilst employing modern techniques to reduce noise.

Regarding original contributions, we must highlight the use of three different kinds of devices, namely, the junction field transistor, the bipolar transistor and the thermionic valve. All these devices were deemed necessary to the design for distinct reasons. It makes sense to incorporate vacuum tubes in an audio applications, for it is highly regarded in this niche field as it has unique sonic characteristics. We must yet highlight that this project seems to be the first instance where modern noise cancellation techniques were used in a hybrid hi-fi audio pre-amplifier. The goal is to be able to achieve partial noise and distortion cancellation as explained in more detail in following chapters.

In the following chapter, further detail is provided on the exact pre-amplifier circuit that is to be developed. Some performance aspects of the pre-amplifier must be considered. These include input and output impedance, THD, nominal gain, and bandwidth. Some of these performance factors will be accounted for in the suggested circuit of the following section.

THEORETICAL DEVELOPMENT OF THE PRE-AMPLIFIER

In previous sections we looked at the main components of this topology: transistors, namely, bipolar junction and junction field-effect, and vacuum tubes. Their behavior in terms of noise has been explored as this is a hi-fi audio application and noise needs to be minimized. This work consists of designing and implementing an audio pre-amplifier with a hybrid configuration using transistors and vacuum tubes utilizing modern practices for noise reduction and cancellation.

Some performance aspects of the pre-amplifier must be considered including input and output impedance, harmonic distortion (THD), nominal gain, and signal bandwidth. These aspects must be assessed and evaluated to ensure that the pre-amplifier is perceived as sounding 'good'. In this field, it seems that one of the most determining criteria is the listener's preference, a subjective parameter [25].

In this chapter, we will delve into the work that was carried out to achieve the desired hybrid hi-fi audio pre-amplifier. We will explain with the most detail all the stages of the pre-amplifier in a more theoretical approach, explaining all the values of the components. spice simulations are also shown, where we can observe the amplification taking place as well as the obtained values for some performance aspects such as the THD and noise. In this chapter, it will be possible to observe the simulations that validate the noise cancelling design with thermionic valves. This is a more theoretical and computer simulation chapter. For the work that went into the perforated board and PCB prototypes of the pre-amplifier consult Chapter 4.

The pre-amplifier circuit will essentially have two channels (stereo) comprising two/three stages which will be further explained in the next subsections. The first stage consists of a common drain, or source follower, buffer stage using junction field effect transistors. This type of device was chosen due to their low noise. The source follower amplifier is

considered a voltage buffer due to the unitary voltage gain. The second stage will rely on a combined equivalent "common-gate + common-source" amplifier with noise cancelling and using 2 triodes. Usually, this "common-gate + common-source" is done using MOS transistors hence the name of the topology. In this work, the interesting and innovative aspect of the design would include this noise-cancelling structure using vacuum tubes. In [24], it is presented one architecture for noise-cancellation which achieves wideband sub-3dB noise figure (NF) while also achieving source matching. In the output stage, a voltage combiner allows for differential to single-ended conversion [24], [26]. The voltage combiner is a single-stage amplifier that is commonly more power efficient and is used to achieve higher gains, using cascading techniques [27]. In Figure 3.1, we can see a schematic with the proposed two stages and the voltage-combiner stage.

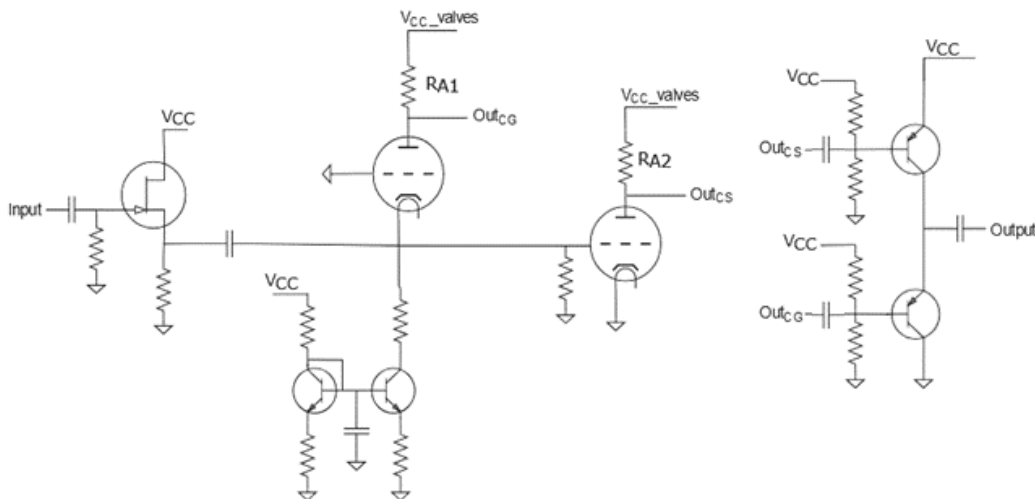


Figure 3.1 - Simplified schematic of the proposed hybrid amplifier.

3.1 JFET Source Follower Topology

As described previously, the first stage of the hybrid audio pre-amplifier consists of a source follower buffer stage using junction field effect transistors, due to their low noise. The common-drain topology has a voltage gain of approximately 1. It has a high input impedance (in the hundred $k\Omega$ range) and low output impedance (In the $1\ \Omega$ to $10\ \Omega$ range). All of these characteristics make it so that it is an ideal topology to use when in need of a voltage unitary gain buffer.

The common drain JFET configuration has a self-bias arrangement which means that the voltage across the source resistor sets the biasing voltage to a negative potential, V_{GS} . The

self-bias arrangement ensures that there's no need to have an additional external source to bias the transistor. In this configuration, no gate current can flow through the reverse-biased gate-source and so we can conclude that the gate current $I_g = 0$ A. The voltage drop at the source is given by applying Ohm's law and so we have $V_S = R_S * I_D$, where I_D corresponds to the drain current.

The operating point is obtained with the expression below. Choosing the adequate value to set the quiescent point sets the JFET in the saturation region. Note that an n-type JFET will start conducting as soon as the voltage between gate and source, V_{GS} , is higher than some negative pinch-off voltage, V_P , that depends on the type of the transistor. For the chosen JFET, the J112, on its *datasheet* it is reported that for a drain to source voltage about 5 V, the $V_{GS}(off)$ minimum is of -1.0V and the max is of about -5.0 V. The designer must then make sure that the source resistor value sets the gate to source voltage above, at least -1.0 V.

$$V_{DS} = V_{DD} - (R_D + R_S) * I_D \quad (3.1)$$

After ensuring that the gate to source voltage is above the $V_{GS}(off)$ (which differs from JFET model to model) and that the drain to source voltage is above the sum of V_{GS} and $V_{GS}(off)$ we are in the active region of the transistor and so the drain current will rise quadratically with VGS according to Equation (2.6).

A simple recipe to set the operating point of a simple source follower (or common drain) topology is to choose a drain current, I_D value. A good starting point would be $I_D = I_{DSS}/2$. Assuming the transistor is in the active region, from the previous equation, we can obtain the value of V_{GS} . The last step would be to choose the value of the source resistor, R_S . We know that the gate to source voltage, V_{GS} is dependent on the value of the drain current, I_D , times the value for the source resistor, R_S . And so, using Ohm's law and knowing the values of I_D and V_{GS} , we can choose the appropriate source resistor, knowing as well that higher resistance values mean that the current noise of the JFET lowers.

If we take a look at the *datasheet* for the selected JFET, the J112 [28], assuming a V_{GS} to be -0.4 V is needed, for a V_{DS} of about 1.2 V then following the gate to drain voltage/drain current graph we should be expecting a drain current of about 7 mA. In our case, we have a drain to source voltage of 9 V which means that for a given 330 Ω source resistor, R_S we have a drain current of about 4 mA and a gate to source voltage of about -1.3 V. Because the input signal is a small signal, we don't need to be too concerned with the output swing and therefore we don't need to have the source voltage at about half of the supply voltage which is the condition that allows for maximum output swing. This will be a concern for the last stage of the pre-amplifier as we will see shortly. Additionally, we included a resistor R_G with a large value to set the DC bias of the junction field-effect transistor gate at 0 V.

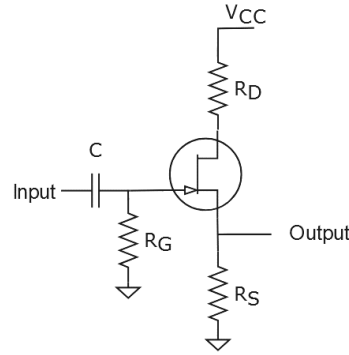


Figure 3.2 - Self Bias JFET input stage.

In Figure 3.3, we can observe the source follower configuration using the J112 field-effect transistor. This is the topology implemented and tested using *LTspice* program. As far as operating point, we have a current drain, I_D , value of 4 mA and a gate to source voltage, V_{GS} of -1.3 V which meets the is above the pinch-off voltage $V_{GS}(\text{off})$ for the J112 which is between -1.0 V and -5.0 V. Furthermore, the drain to source voltage, V_{DS} is above the sum of V_{GS} and $V_{GS}(\text{off})$ and so the transistor is biased to be in the active region.

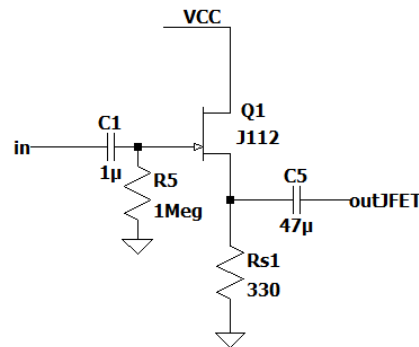


Figure 3.3 - Source follower implemented in *LTspice* program.

Below, in Figure 3.4, we can observe the result of the voltage buffer achieved. As we can observe with the red line, the voltage gain is slightly below one. This is expected because the voltage gain, that can be observed below, depends on the value of g_m that is set with the DC bias and the source resistor value, R_s . Independently, of the values of the source resistor and of the transconductance, g_m , the voltage gain will be approximately one given the product of R_s times g_m is much bigger than 1 V/V.

$$\frac{v}{v_i} = G_v = \frac{g_m R_s}{1 + g_m R_s} \quad (3.2)$$

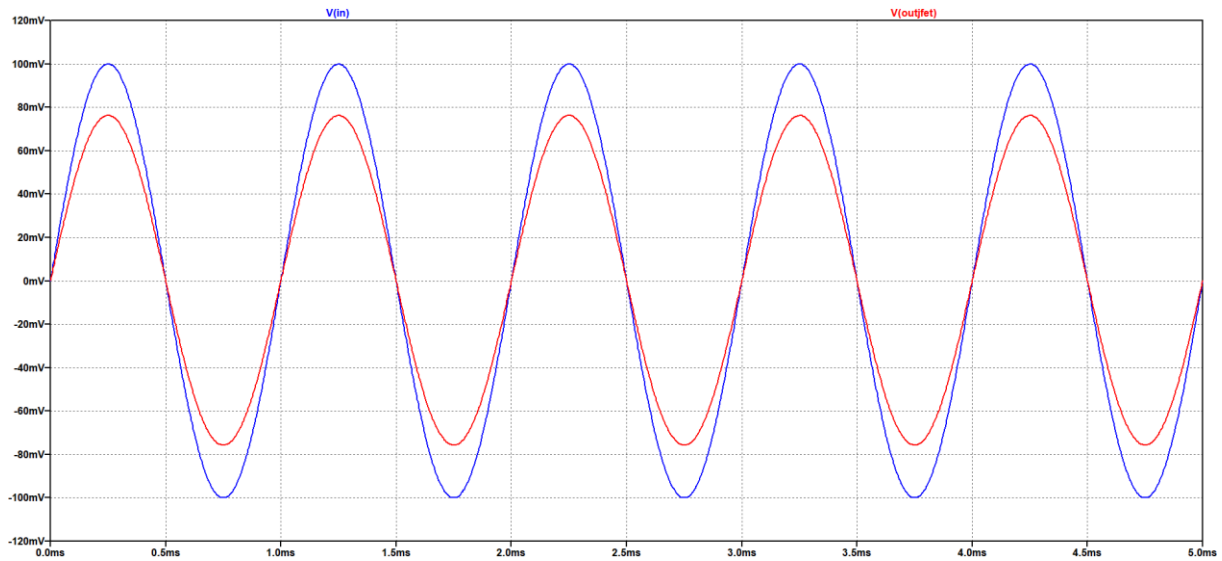


Figure 3.4 - Voltage gain of the source follower.

The voltage gain of this input stage is of about 0.8 V/V , the input impedance is of about $1 \text{ M}\Omega$ and the output impedance corresponds to $330 \text{ }\Omega$. In terms of noise, using the `.noise` command in *LTspice* program we obtain an RMS (root mean square) value of about $137.59 \text{ }\mu\text{V}$. These are all the performance aspects relevant for this stage. In terms of total harmonic distortion, through the `.four` analysis in *LTspice* the value of the first stage corresponds to 0.167845% (0.177897%).

This concludes the explanation of the values for the 1st stage of the hi-fi audio pre-amplifier. In this subsection we delve into how the values for biasing the JFET were chosen and some considerations that were taken with noise. Additionally, we've seen that the computer simulations are within expected.

3.2 Noise Cancelling with Vacuum Tubes

In this subsection will deal with arguably the most important part of the hi-fi audio pre-amplifier using vacuum tubes and transistors. As previously mentioned, in this work, one of the main objectives consists of performing partial noise and distortion cancellation.

The noise cancelling stage is achieved by the combination of a common-gate (CG) stage and a common-source (CS) stage. This is a well-known structure which has been first found in the literature about 15 (fifteen) years ago. The traditional way of implementing this structure states that the devices should have identical size and bias for the CG and CS stages. This structure allows for a low NF (noise figure), since the thermal noise of the device in a common gate configuration is canceled out. The noise produced by the common gate topology appears in phase at the two outputs terminals, while their signals are in opposition. It is possible then to obtain double the gain and cancel noise. It's important to mention that the presented solution

is the one that allows for the best noise figure however, it is applicable and valid over a wide band of frequencies and therefore suited for our audio application and many others, such as RF.

The [23] paper serves as inspiration to implement this topology. Three different design options are presented and compared between each other. It was found that for the third design option, the NF (dB) is the lowest, the gain is constant and reaches about 18 dB whilst the output gain imbalance corresponds to 0 dB. The output gain imbalance corresponds to the ratio of voltage gain of the CS and the CG stage. The gain required in the CS-stage to cancel the distortion products of the CG-device equals the gain required to obtain output balancing leading to the conclusion that simultaneous balancing and cancellation of unwanted noise and distortion currents of the CG transistor is possible (consult Chapter 2 for the more in-depth look into this work).

Regardless of the third design achieving a better noise figure whilst making sure that the gain imbalance is 0 dB, i.e., that the gain at the output of both common-gate and common-source stages is the same, we opted to implement the traditional combination of a common-gate (CG) stage and a common-source (CS) stage where both load resistors and transconductances are equal for both stages. Having never utilized this topology and vacuum tubes, we thought that implementing the noise cancelling the traditional way and verifying that it does work with vacuum tubes would be wiser provided that, on a later date, or simply a version 2 prototype, the noise cancelling be implemented with the best approach. Such approach is extensively (described in Chapter 2) and corresponds to having the CS stage be admittance-scaled to the CG stage.

We've seen in Chapter 2 that vacuum tubes are three terminal devices such as MOSFETs and behave similarly. The idea to implement the noise cancelling using vacuum tubes arose from observing the similar behavior of such devices. The noise cancelling topology was implemented with both thermionic valves having the same anode load resistors. A common value that is seen for the anode load resistors, R_a , is 100 kOhm. Note however that, most pre-amplifiers deal with high-tension supply voltages of 200 V DC to 400 V DC. We will be using 100 V DC as it is intended to have a working prototype, and we assumed it would be a relevant voltage to have the valves working and displaying their non-linear behavior and amplifying significantly without compromising safety. Working with voltages above 60 V DC is dangerous and may cause serious harm. The 100 V DC power supply value presents itself as good compromise between safety of implementation of prototypes and obtaining decent result in terms of sound from these devices. More details regarding the prototypes can be found in Chapter 4.

For a 100 k Ω anode load resistor, R_a and a high-voltage supply of 100 V and performing the load line analysis we can obtain the maximum anode current that will always flow in the

valve. Assuming there is no current through the valve, then, there is no voltage drop across the valve. We mark the first point in the anode characteristics graph where $V_a = 100$ V and $I_a = 0$ mA. Assuming then, that there is the voltage across the valve given by the high voltage supply then, using Ohm's law, $V_a = I_a * R_a \Leftrightarrow \frac{V_a}{R_a} = I_a \Leftrightarrow I_a = \frac{100}{100k\Omega} = 1$ mA. Having these two points and by consulting the datasheet of the ECC83/12AX7 double triode [12], we can draw the load line using the anode characteristics of the valve [11].

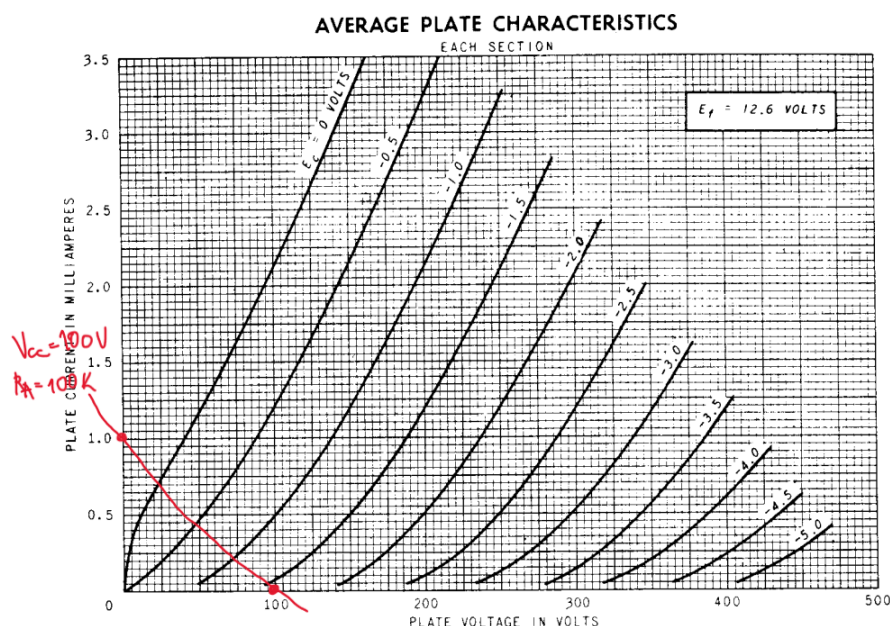


Figure 3.5 - Load line analysis performed for the ECC83/12AX7 valve [12], [13].

This load line analysis is described in further detail in Chapter 2. The values for the anode resistors used in the design of the pre-amplifier are of the same as the ones present in the load line analysis of Chapter 2. Note that our high-tension supply is of 100 V DC.

The next step is to set the grid to cathode voltage to finish setting the quiescent point of the pre-amplifier. Typically, in hi-fi audio the V_{gk} is set to have the most output swing and so that implies that it sits in the middle of the previous graph. That corresponds to having the grid to cathode voltage, V_{gk} be approximately -1.3 V. This can be done through several ways. The simplest one, however it reduces the output swing is by forcing a voltage drop across a cathode resistor, R_k . This resistor should be bypassed by a capacitor so that in AC it should not affect the voltage gain of the stage whilst simultaneously setting the operating point. For a V_{gk} of about -1.3 V the quiescent current that flows in the valve corresponds to 0.8 mA.

In Figure 3.6, we can observe the circuit implemented. We can observe the noise cancelling topology implemented with the same anode load resistors, R_a , for both the common

grid, also referred to as grounded grid, and the common cathode stages. Note however that the V_{gk} for both triodes, is of about 0 V.

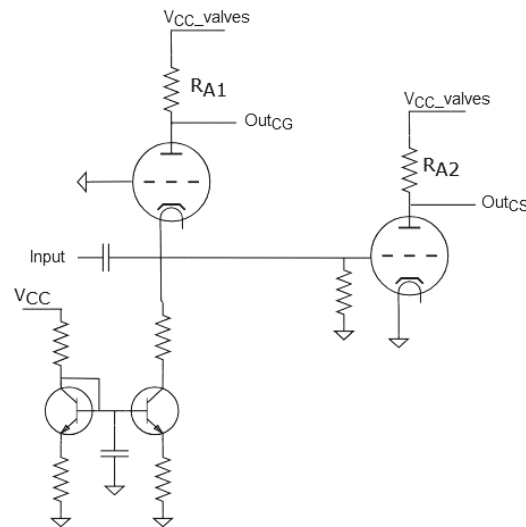


Figure 3.6 - Second stage of the pre-amplifier - noise cancelling topology.

Moreover, the following results are for every stage on its own. In this case, the voltage buffer is not AC coupled to this stage in the following results. Based on the results shown in the previous subsection, however, we can anticipate that, by joining the two first stages, we will see the voltage gain reduced by about 20 % of what is shown in Figure 3.7 below. As can be observed, for a 200 mV peak-to-peak input signal which is fed in the cathode of the grounded grid (GG) and in the grid of the common cathode (CC), both outputs (labeled as 'outCG' and 'outCS') have equal gain and having a peak-to-peak voltage of 12 V. The simple calculations done by dividing the output and input voltages, result in a theoretical voltage gain of 60 V/V which corresponds to about 36 dB.

It can also be observed that the grounded grid output signal ('outCG') is in-phase with the input signal whilst the common cathode output signal ('outCS') has an inverted phase, an 180° phase shift to that of the input signal. This is expected as the common cathode is an inverting topology and this is what makes the partial noise and distortion canceling possible, as will be shown shortly. The basic principle is described in more detail in Chapter 2 but consists of the input signal being fed through the cathode of the grounded grid and through the grid of the common cathode. The signal that is fed through the grid of the common cathode, however, has the contribution of noise from the grounded grid device and so, when both signals are added, by the voltage combiner, the noise contribution from the grounded grid is canceled and, by adding the two signals, the gain is doubled, assuming a great output impedance. In

audio, the device that follows a pre-amplifier is referred to as a power amplifier which has a input impedance of about 100 kOhm.

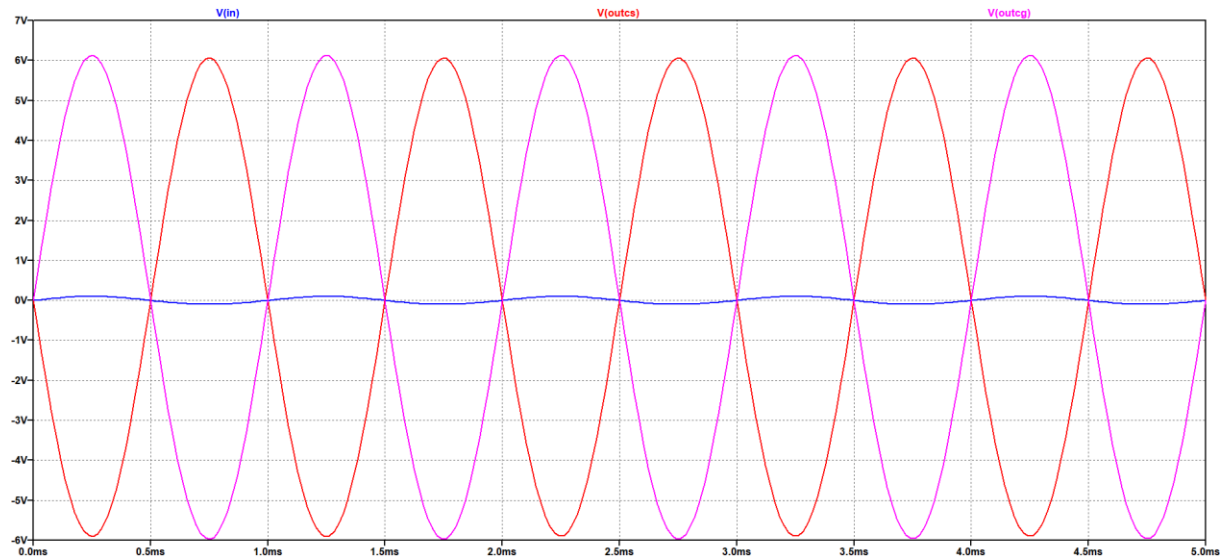


Figure 3.7 - Noise cancelling topology: output.

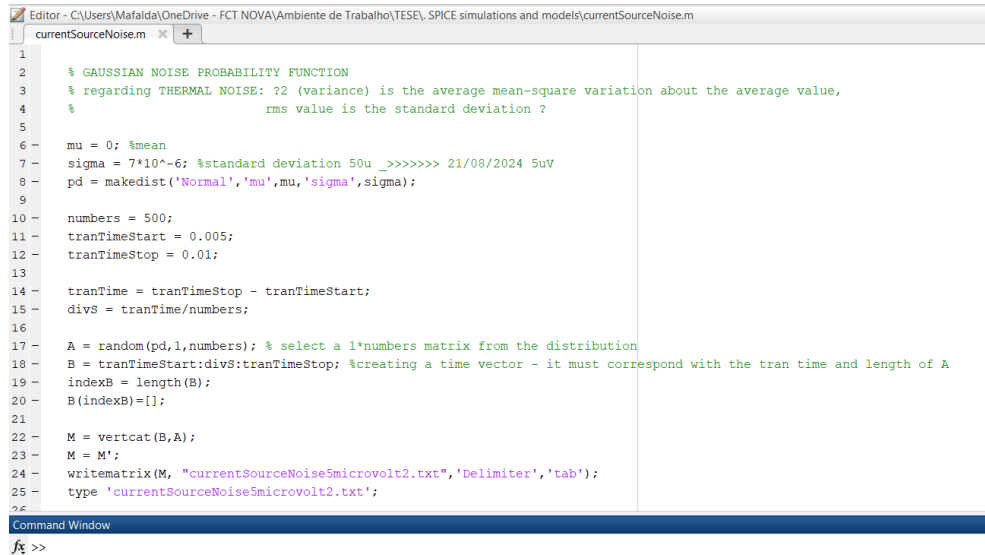
Having verified that we have equal gain for both outputs, the next step consists of observing the partial noise cancelling. The thermal noise produced by the grounded grid stage can be represented by a current source, originating then, a voltage noise at the input since it flows across the cathode resistor. And, as mentioned previously, this noise voltage is obtained in-phase at both the ground grid and common cathode outputs.

To verify that the topology was correctly designed, a signal must be fed in parallel with the anode and cathode of both triodes. This signal approximates the thermal noise created by vacuum tubes which has equal power across all frequencies [19], [29], [30].

Experimentally, one option for simulating the thermal noise generated by vacuum tubes consists of generating the thermal noise with a Gaussian distribution and import it into *LTspice* program using the PWF option available for voltage and current sources. The PWF file format has a specific structure which corresponds to a matrix with two columns [31].

Using MATLAB and the *makedist* function, we generate a Normal Distribution, defining the mean as 0 (zero) and the standard deviation (δ) as 5 μ V, as we can observe by Figure 3.8. After that, we must select a certain number of values and create their corresponding time vector in order for it to be compatible with the PWF file format [31]. In this case, we chose 1000 (thousand) values from the normal distribution and, according to the transient command that is being run in *LTspice* program, one must create the respective time vector. Note that, if the *LTspice* directive we're running corresponds to *.tran 0 0.1 0 0.1*, this means that the time

vector created in MATLAB must only be from 0 to 0.1 seconds. This is important to reiterate so that the noise must be added to the input signal during the full transient simulation.



```

1
2 % GAUSSIAN NOISE PROBABILITY FUNCTION
3 % regarding THERMAL NOISE: ?2 (variance) is the average mean-square variation about the average value,
4 % rms value is the standard deviation ?
5
6 mu = 0; %mean
7 sigma = 7*10^-6; %standard deviation 50u _>>>>>> 21/08/2024 5uV
8 pd = makedist('Normal','mu',mu,'sigma',sigma);
9
10 numbers = 500;
11 tranTimeStart = 0.005;
12 tranTimeStop = 0.01;
13
14 tranTime = tranTimeStop - tranTimeStart;
15 divS = tranTime/numbers;
16
17 A = random(pd,1,numbers); % select a 1*numbers matrix from the distribution
18 B = tranTimeStart:divS:tranTimeStop; %creating a time vector - it must correspond with the tran time and length of A
19 indexB = length(B);
20 B(indexB)=[];
21
22 M = vertcat(B,A);
23 M = M';
24 writematrix(M, "currentSourceNoise5microvolt2.txt",'Delimiter','tab');
25 type 'currentSourceNoise5microvolt2.txt';
26
Command Window
fx >>

```

Figure 3.8 - MATLAB script to generate thermal noise of vacuum tubes.

Below, we can also observe the result of the generated MATLAB .txt file with the Gaussian distribution noise signal and its corresponding time vector can be observed. Note that it must obey the PWF file format to be correctly imported and interpreted by *LTspice* simulator.

```

0      -6.93145480863842e-06
4e-05  2.1601030302081e-05
8e-05  0.000112649676384852
0.00012 -2.29790286045643e-05
0.00016 4.52435498450868e-06
0.0002  0.000130406748761287
0.00024 -5.18584623098382e-05
0.00028 1.26552082692513e-05
0.00032 -1.33299428880973e-05
0.00036 6.58741892548127e-05
0.0004  5.58507455051929e-06
0.00044 6.35718353465617e-05
0.00048 2.0588962153999e-05
0.00052 3.78958230064067e-05
0.00056 -8.36167547172254e-05
0.0006  -3.66742737231358e-05
0.00064 -6.61607251375474e-05
0.00068 -7.55782284405887e-05

```

Figure 3.9 - Illustration of the PWF file format used to create the gaussian noise signal in the *LTspice* program.

In Figure 3.10, we can observe the circuit with the previously mentioned current sources in the PWF file function. The *currentSourceNoise5microvolt.txt* and

currentSourceNoise5microvolt2.txt files were both generated using the *makedist* function with slightly different parameters to mimic the slightly different thermal noise profile that the two devices exhibit.

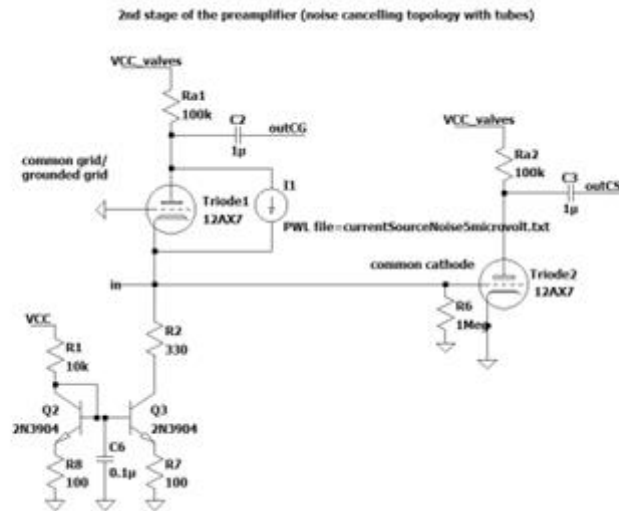


Figure 3.10 - Circuit to test the partial noise and distortion cancelling.

By running a transient simulation, we can observe in Figure 3.11 that the output of the common grid triode has the noise contribution with the expected behavior. The signal in blue corresponds to the input signal which, again, is fed directly only to this stage. Only in the last subsection of this chapter will we observe all the stages properly AC coupled and working together.

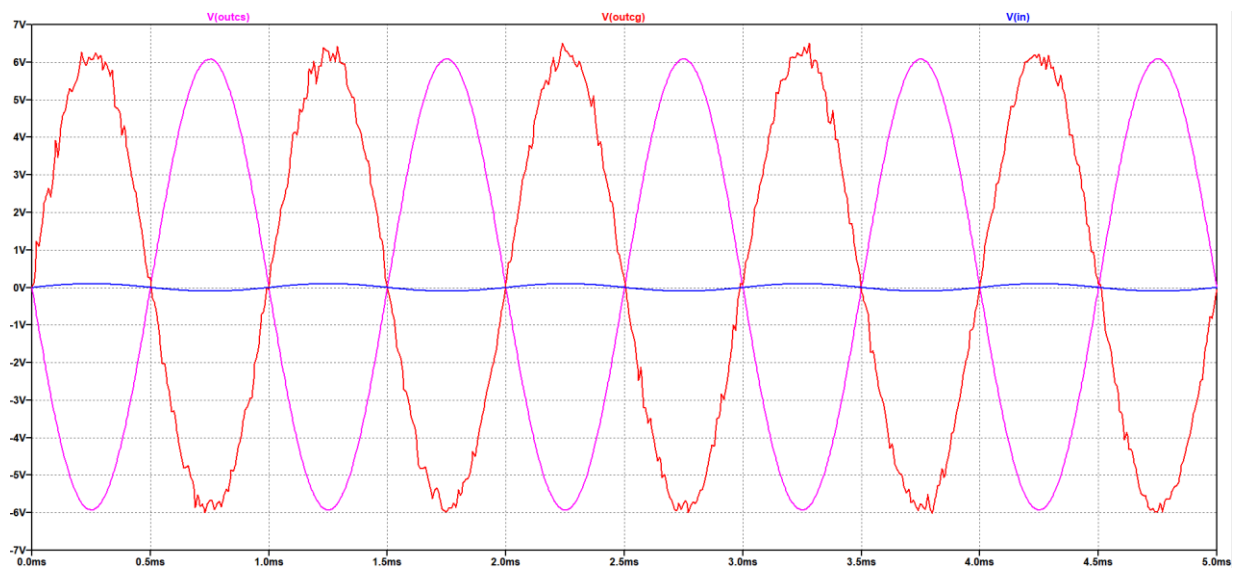


Figure 3.11 - Output of both triodes with the noise contribution.

In Figure 3.12, we added another trace to the plot, in dark green, which corresponds to the sum of the output of the grounded grid ("outCG") with the output of the common cathode ("outCS"). As we can observe, the result is a signal with greater gain and in-phase with the input signal, in blue. Note that the final stage of the pre-amplifier corresponds to the voltage combiner which should perform the adding of the outputs of the triodes. In the following subsection we will observe that the output of the voltage combiner will have the same behavior as the dark green line in Figure 3.12, therefore validating the partial noise and distortion cancelling structure and capability of the proposed pre-amplifier.

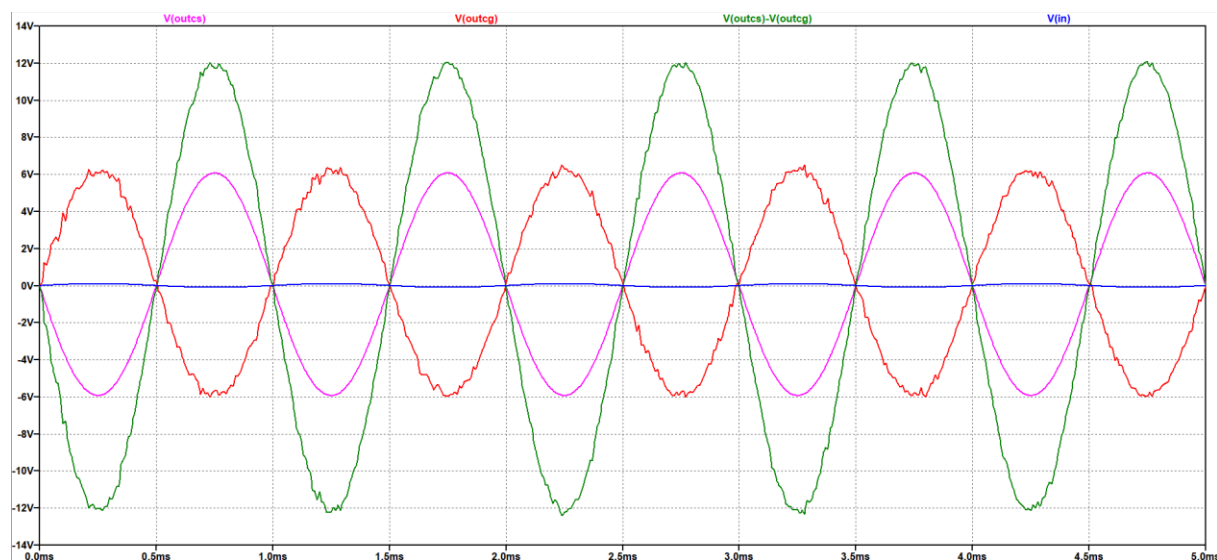


Figure 3.12 - Output of both triodes summed, in dark green.

In terms of performance aspects for this stage, we have that the input impedance is very high to accommodate the low output impedance of the source follower from the first stage. The output impedance corresponds to the parallel of the internal resistance of both triodes with their respective anode load resistors, which corresponds to about $100\text{ k}\Omega$. The noise contribution of this stage corresponds to the sum of both outputs, resulting in a value of about $42\text{ }\mu\text{V}$. The voltage gain is about 60 V/V , although a lower value is to be expected when both the first and second stages are AC coupled and working together. In terms of total harmonic distortion, the value is about 0.8% summing the values of THD at both outputs. In more detail, the output of the grounded grid contributes with a THD percentage of 0.219134% (0.227337%). The output of the common cathode contributes with a THD percentage of 0.611649% (0.614627%). Both outputs contribute with similar noise values of about $20\text{ }\mu\text{V}$.

This concludes the theoretical explanation of the second stage of the hi-fi hybrid audio pre-amplifier which should, at its output, have two signals with equal gain and opposing phases which was achieved through a grounded grid and common cathode structure. Both

differential signals should be then added, which will be discussed in the following subsection, as to complete the partial noise and distortion canceling.

3.3 Voltage Combiner Topology

In this subsection we will discuss the voltage combiner structure. It is responsible for the conversion of differential to single-ended signals. This stage will add the two differential signals and therefore conclude the partial noise and distortion cancelation. When adding the two signals, the gain is doubled, and the noise is reduced by the mechanism we explained in the previous subsection.

It is assumed that the size of the transistor M1 is identical to that of the M2 for the output balancing without gain and phase mismatches, and both transistors are in saturation [32], [33]. Since the same current flows from the transistor M1 to M2, the gate overdrive voltage of the transistor M1 is identical to that of the M2 so that the single-ended output voltage so that is given as shown in Equation (3.3).

$$v_{out} \cong v_{in} - (-v_{in}) = 2 \cdot v_{in} \quad (3.3)$$

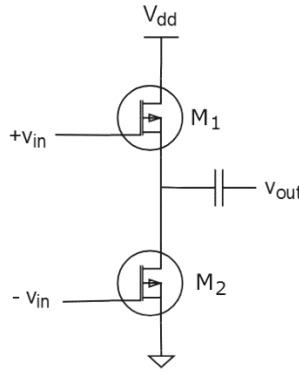


Figure 3.13 - Voltage combiner topology.

The basic mechanism is explained above however, note that we chose to implement this structure with bipolar junction transistors. The simplicity of these components and very well studied behavior made it so, when trying to understand and implement this structure, we chose to do so using very predictable components.

Making sure that the base to emitter voltages are above 0.7 V and choosing a collector current value that flows through both devices set the transistors in the active region. By choosing a rather simple self-bias arrangement, the needed voltage drop occurs between the base and emitter of both devices, as shown in Figure 3.14.

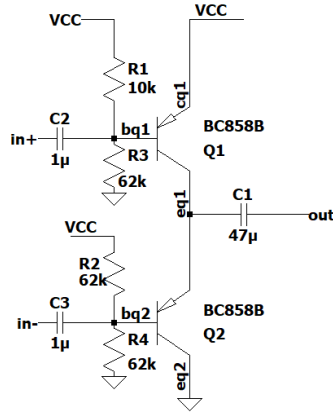


Figure 3.14 - Voltage Combiner structure implemented in *LTspice*.

For the configuration present in Figure 3.14, the DC operating point shows that the collector current flowing in both transistors is of about 16.8 mA. The emitter current is a replica of the collector current, as shown in Equation (3.4):

$$I_E = I_C + I_B = I_C \left(1 + \frac{1}{\beta}\right) = I_C + I_C/\beta \quad (3.4)$$

The base current, I_B corresponds to the ratio between collector current I_C by the current gain β (or h_{fe}). The value of base current corresponds to 0.059 mA. This means that β is approximately 285 for this biasing scheme and for the PNP bipolar junction transistor model chosen [34]. For the source follower, the V_{be} is above 0.7 V and the same happens for the common emitter, as expected. The DC operating point is valid, and we must now verify the behavior when fed with the small signal inputs.

In Figure 3.15, and for 200 mV peak-to-peak sinusoidal input signals that are directly generated from an ideal voltage source, the result is a 400 mV peak-to-peak output signal, therefore validating the design using bipolar junction transistors. Note that “in+” and “in-” have opposing phases, simulating the expected output from the grounded grid and common cathode structure. The total harmonic distortion of this structure is the sum of the contributions of both inputs “in+” and “in-” which are equal and have a value of 0.353335 % (2.154410 %).

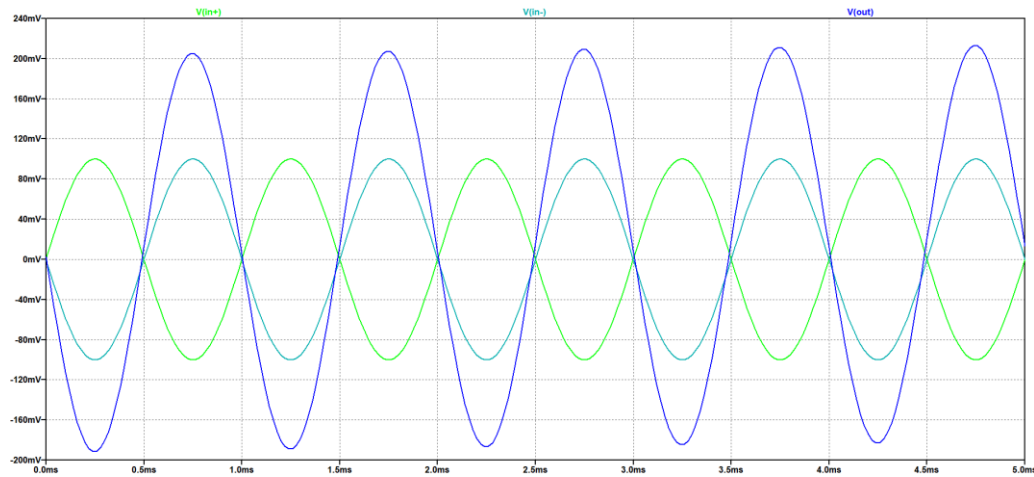


Figure 3.15 - Validating through simulations the voltage combiner structure for a 100 mV input signal.

One issue that was verified is that, as seen from the previous subsection, the voltage swing of the previous stage is very significant due to the amplification of the triodes. This means that, the voltage combiner must also support that voltage swing as to not heavily distort the output signal. As we can observe in Figure 3.16, for a 500 mV peak-to-peak sinusoidal signal, the output of the voltage combiner is heavily distorted in the positive swing. How may we solve this? By ensuring that the collector to emitter voltages allow for this voltage swing. The ideal value for the source follower structure should at $V_{CC}/2 + V_{CC}/4$ and the common emitter should sit at $V_{CC}/2 - V_{CC}/4$. This is because we have two devices that will essentially only be able to swing from 0 to $V_{CC}/2$. Furthermore, both V_{BE} voltage drops should be ensured. If we were only supplying a device with 9 V, then that would make it so that the available output swing, given that the device is adequately biased at $V_{CC}/2$, that would make it so that the available output swing is of about 8 V peak-to-peak.

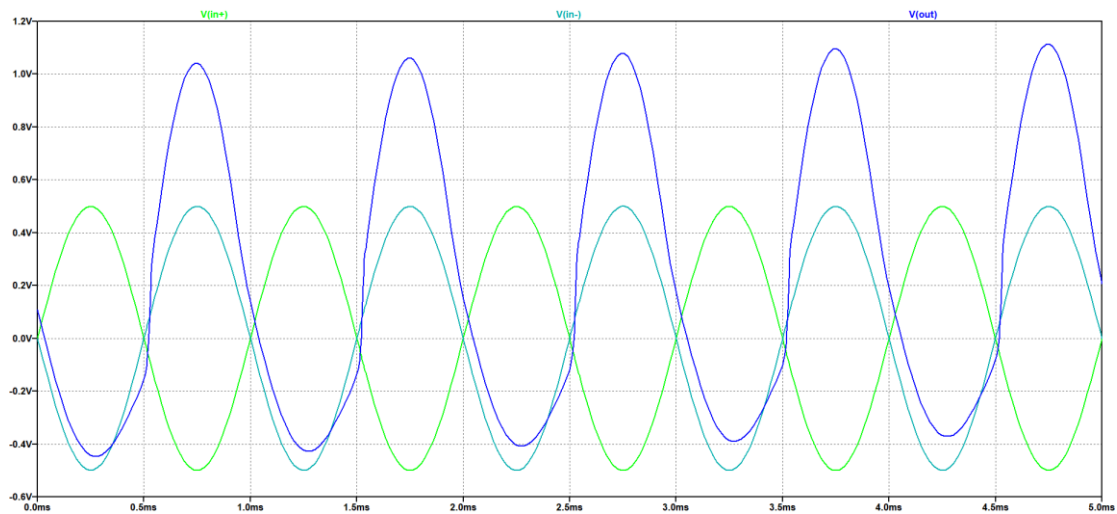


Figure 3.16 - Voltage combiner behavior for a 500 mV peak-to-peak input signal.

One problem starts to arise due to loading effects, when joining both the second and third stages. Firstly, the output impedance of the previous stage is only of about 100 k Ω and when joined with the third stage, the impedance will drop significantly, meaning that the voltage gain will be lower. Having the input impedance of the third stage be of about 10 k Ω and having them in parallel with 100 k Ω means that the resulting impedance will be about 10 k Ω , attenuating the signal. This solution however is the one that provides an acceptable total harmonic distortion for all the stages, as we will see in the next subsection whilst simultaneously allowing for the gain of the pre-amplifier to be above 20 dB as was intended.

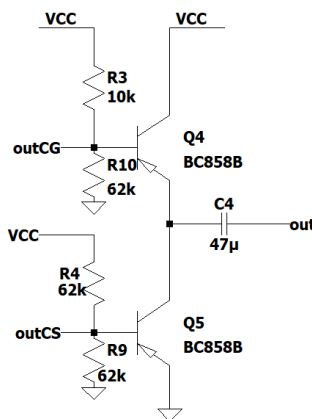


Figure 3.17 - Final version of the voltage combiner.

Nevertheless, the presented solution of Figure 3.17 achieves the best result. When coupling the two stages we will observe that the third stage is performing the partial noise and distortion canceling, further validating this solution. Again, the "*vout+*" signal has the contribution of the noise from the first device and "*vout-*" also has that same noise contribution. The noise appears in phase at the output of both devices. When the sum of both signals occurs, the noise contribution of the common grid device is cancelled. This is verified at the output of the voltage combiner as will be shown shortly.

In terms of performance aspects, the noise that is added by this topology is the sum of the differential inputs and it has a value of about 28.7 μ V. Furthermore, the total harmonic distortion of this stage is the sum of the differential inputs, and it has a simulated value of about 1%.

In the following subsection, we will analyze the performance aspects of the hybrid hi-fi audio pre-amplifier and offer some modifications that could be done for future versions of the pre-amplifier. In Chapter 4, the development of the will be explained, and we will take a look at the many considerations that were had leading to, in some cases, some modifications of the design.

3.4 Computer Simulations of the complete Pre-Amplifier: Final Performance Aspects

In this subsection, the final performance aspects that were achieved for the complete hybrid hi-fi audio pre-amplifier are presented. In terms of theoretical design, it is important to highlight the use of three different types of devices, namely, vacuum tubes, junction field effect transistors and bipolar junction transistors. The validated the CG-CS partial noise and distortion canceling with vacuum tubes is shown, fulfilling the main objectives of this work.

In Figure 3.18, we can observe the final circuit that performed the best, having a low total harmonic distortion, THD, low noise and a voltage gain of 28 dB as well as having a relatively flat response in the 20 to 20 kHz frequency range.

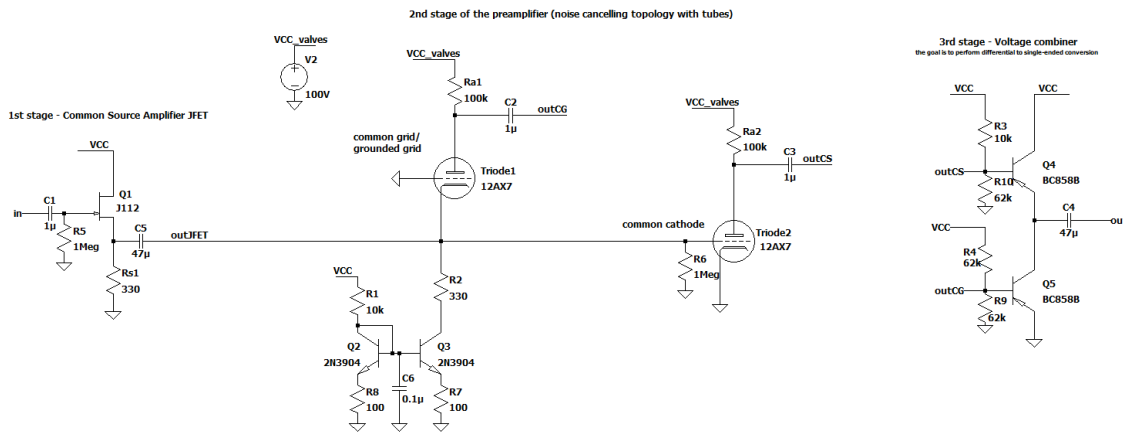


Figure 3.18 - Hybrid hi-fi Audio pre-amplifier implemented in *LTspice*.

There is one structure that wasn't properly looked at in previous subsections as it an accessory to the proper function of the pre-amplifier. That is the current mirror implemented with bipolar junction transistors. The current mirror is designed to copy a current through one active device by controlling the current in another active device of a circuit. The output current should not be affected by the load, by all means.

The current mirror should provide, in our case, the needed current to the vacuum tube. Based on the load line analysis seen in a previous subsection, this current will be of about 0.5 mA and so, the current mirror was designed to be able to supply such current. This structure is two active devices cascaded, one of them in diode configuration. The transistor in the diode configuration provides the voltage needed to the base to have both transistors in the active region. Provided that they're matched, i.e., have most of the same device properties, then the emitter current set by the transistor in diode configuration, will be matched in the other

transistor. The output current of the current mirror will then correspond to the collector current of the transistor in diode configuration.

The emitter degeneration of both transistors [35] helps with linearity of this topology and as to not affect the voltage gain, they are decoupled by means of a sufficiently large capacitor.

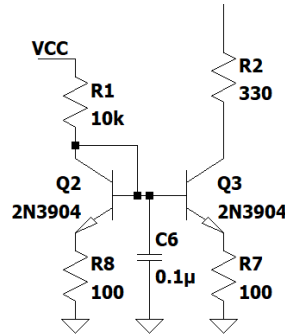


Figure 3.19 - Current mirror implemented in *LTspice*.

In Figure 3.19, we can observe the circuit corresponding to the current mirror that has been implemented. From the load line analysis, we know that a current of about 0.5mA is needed for the triode. The supply voltage corresponds to 9 V and to force this collector current, we introduced a 10 kOhm resistor at the collector of the transistor in diode configuration. The resulting collector current should be of about 9 mA. However, in the *LTspice .op* analysis it corresponds to 0.7 mA. With emitter degeneration, the mirrored collector current that appears in the other active device has a slightly lower value to the value of collector current just mentioned.

Now we must look at the performance aspects of the pre-amplifier present in Figure 3.18. All simulated performance parameters were obtained for an input signal of 200 mV peak to peak. Regarding total harmonic distortion, with all the stages, the *.four* command which calculates the contribution of all harmonics to the total harmonic distortion, gives a value of 0.520379 % (0.531978 %). A pre-amplifier should have a THD below 1 %, which we achieved for a 200 mV peak-to-peak input signal.

Regarding noise, with all the stages, the *.noise* command calculates the total RMS noise contribution of the pre-amplifier. The total RMS value is reported to be 3.79 mV.

It was previously mentioned that the pre-amplifier and more notably hi-fi audio pre-amplifiers should have a flat frequency response in the 20 to 20 kHz range. In Figure 3.20, we can observe that at 20 Hz, the voltage gain is of about 27.8 dB, a little below its reference value of 28.6 dB. There is some loss in the low frequencies, between 20 and 80 Hz, however, it shouldn't be perceptible to most inexperienced listeners.

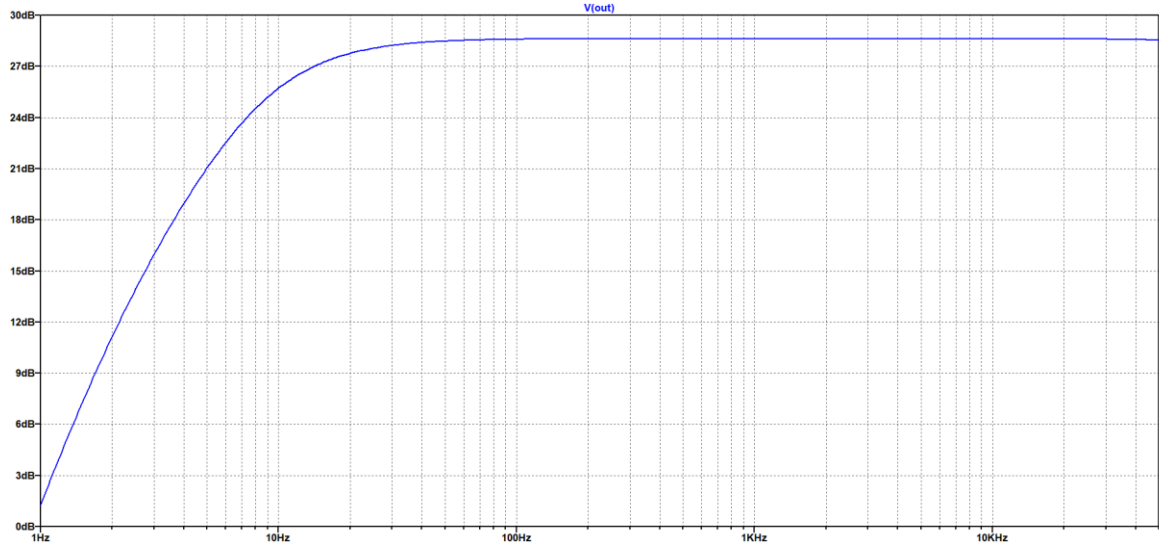


Figure 3.20 - Hi-fi audio pre-amplifier AC analysis.

This is a very good result in terms of AC response, and it was possible to achieve due to the use of electrolytic capacitors in the prototypes, as we will see in the next chapter. Lastly, we validate the full design with respect to the partial noise and distortion cancelling of the pre-amplifier.

The experimental method of introducing and simulating the noise has been explained with further detail in subsection 3.2. To validate the partial noise and distortion canceling of the pre-amplifier we performed the same steps. Created a Gaussian distribution signal and its corresponding time vector, given that the time vector must correspond with the *.trans* simulation we're running in order to affect the signal during the whole of the simulation. Similarly, we introduce the current sources in parallel with the triodes, placing them in between the anode and cathode of the devices and import the PWF files generated in MATLAB, as shown in Figure 3.21.

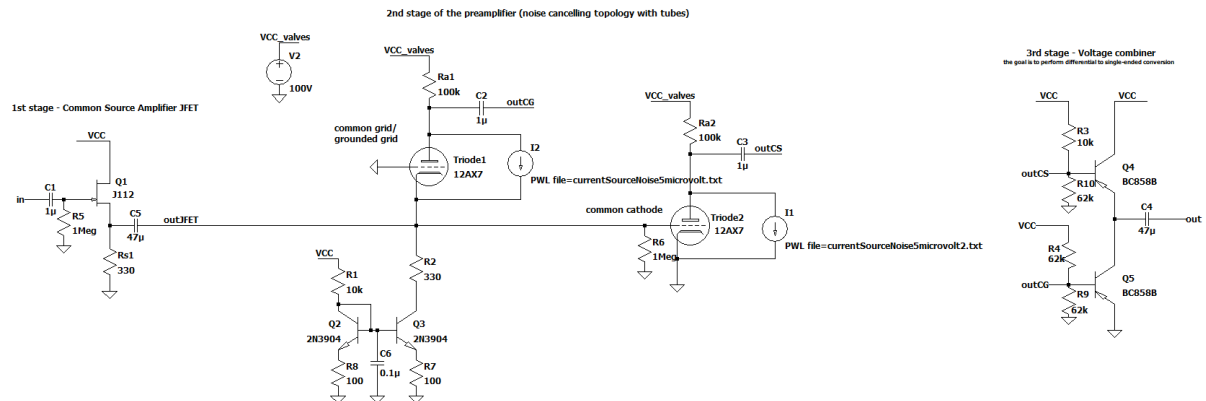


Figure 3.21 - Circuit implemented for the noise cancelling topology in LTspice.

In Figure 3.22, the simulated output of the three stages is shown, in blue. In red, the sum of the output of the grounded grid with the output of the common cathode. As we can observe, the output of the pre-amplifier corresponds to performing the sum of both signals, validating that the voltage combiner is, in fact adding the two signals, and therefore, executing the partial noise and distortion cancellation. Note that the offset is due to the supply voltages of the voltage combiner that help set the bipolar junction transistors in the saturation region.

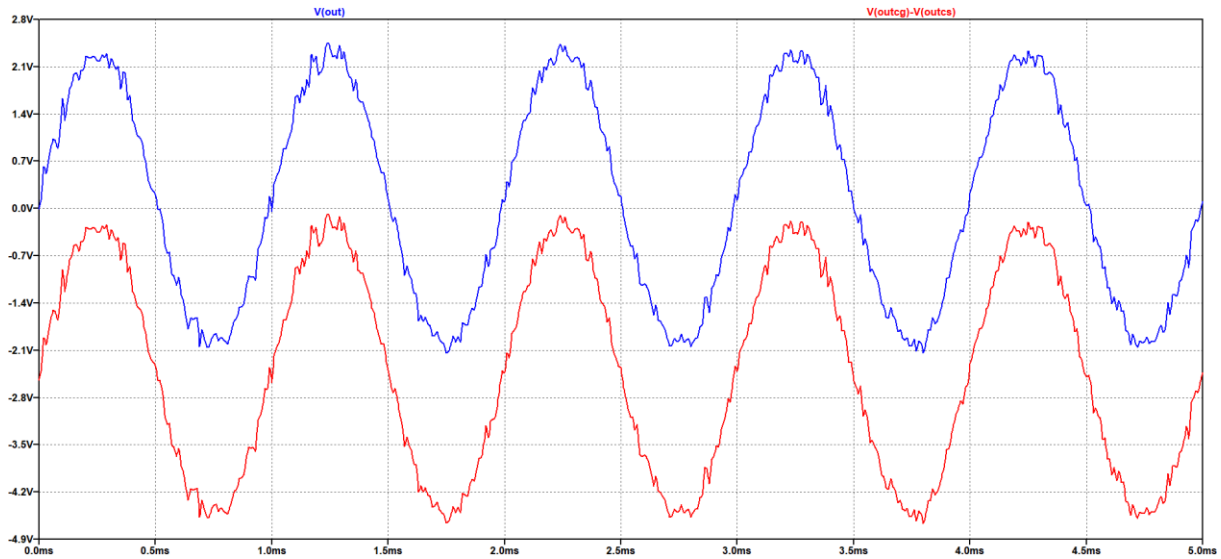


Figure 3.22 - Output of the pre-amplifier vs. ($V_{outcg} - V_{outcs}$).

This concludes the theoretical analysis of the hybrid hi-fi audio pre-amplifier in which the main objectives of this work were achieved. Such objectives were the validation of the noise cancellation structure using vacuum tubes and employing several types of devices in their most efficient way. The next chapter will deal with the physical implementation of the pre-amplifier using two distinct platforms. The perforated board prototype was used simply to validate the *LTspice* results obtained and to confirm that all the different stages worked as expected. Furthermore, this prototype was used to fully understand how to use vacuum tubes and how to power them adequately, given that the triode filaments, for example, are heated indirectly and need a separate power supply. Additionally, a PCB prototype was developed and the designing process as well as the assembling will be thoroughly explained in the following chapter, as well as the obtained laboratory results for the prototypes.

PRACTICAL DEVELOPMENT OF THE PRE-AMPLIFIER

The previous chapter focused on the theoretical approach and corresponding computer simulations for the hybrid hi-fi audio pre-amplifier. Each stage was thoroughly analyzed, outlining its contribution to the overall design. This chapter addresses the physical implementation of the pre-amplifier, including power considerations. It will explain why the pre-amplifier is powered by two distinct power supplies—one providing 12 V and another 100 V—and the necessity of voltage regulators.

Two prototypes were constructed. One using perforated board and another in printed circuit board (PCB). The perforated board was initially used to validate the behavior observed in *LTspice* simulations and served as a platform for experimenting with different component values before finalizing the design for the PCB version. Having never worked with vacuum tubes, it served as the ideal platform to learn how to power the valves and their respective filaments. It provided valuable insights into potential modifications for the PCB design. One important contribution was realizing that the LM317T [36], an adjustable voltage regulator, heats up significantly when supplying 300 mA of current to the valve. This realization prompted design adjustments for the PCB, including isolating the LM317T from the rest of the board and incorporating a dedicated space for a heat sink to manage its heat dissipation effectively.

Regarding the design, it is important to note that the pre-amplifier will be a stereo amplifier. This means that the circuit in Figure 4.1 will need to be replicated twice—once for each stereo channel (Right and Left). However, for the perforated board prototype, we only implemented the circuit once, effectively simulating either the Right (R) or Left (L) channel. This prototype was simply a platform to validate the design and confirm that the results matched the simulations performed in *LTspice* program, ensuring no surprises when testing the printed circuit board (PCB).

Following the lessons learned from these prototypes, we will now discuss their results. Since the perforated board was simply a learning and validating platform, we will confirm its functioning rather than delve deeply into performance metrics. Each stage of the circuit will be evaluated to ensure it is modifying the input signal as expected. The source follower implemented with a junction field effect transistor (JFET) should attenuate the signal as seen in the previous chapter, followed by the significant amplification provided by the vacuum tubes. The output of this stage should result in two sinusoidal signals with equal voltage gain and opposing phases. The voltage combiner should then join both signals and the resulting voltage gain should be of about 23 dB.

Due to the rudimentary nature of the perforated board prototype, certain parameters—such as noise—are not relevant for detailed measurement at this stage. Auxiliar wires used to monitor signals via an oscilloscope may act as antennas, increasing circuit noise. Measurements of noise, total harmonic distortion (THD), and the frequency response of the pre-amplifier will only be taken with the PCB prototype.

It is noteworthy that the PCB prototype reflects my limited experience with printed circuit board design. There is room for improvement even beyond the second iteration of the PCB discussed in subsection 5.1. Having had some help and supervision, the board is the sum of my efforts in learning the *KiCad* design tool with some guidance from the professors.

The following subsections will cover the physical and design considerations that made it possible the creation of the perforated board and PCB working prototypes. The results obtained in the laboratory for the perforated board and printed circuit board prototypes will also be present in this chapter. This will conclude the detailed explanation of the work done to achieve the hybrid hi-fi audio pre-amplifier to achieve partial noise cancelation using both transistors and vacuum tubes.

4.1 Perforated Board Prototype

The perforated board prototype served as an important platform to attest to the functioning of the design. Since it was the first time working with vacuum tubes, it was crucial to understand how to properly power the filament. Furthermore, it helped to better understand the power needs of the whole design which are as follows.

Initially, we had only planned for a 100 V DC high-voltage supply to power the valves and a 9 V DC supply for the solid-state components [37]. However, while constructing the bill of materials for the perforated board, an additional requirement was discovered: a 6.3 V DC supply with 300 mA for the vacuum tube filaments. This need was not accounted for in the *LTspice* simulations, which don't consider the filament power requirements for the valves.

This discovery was critical, as it highlighted that previously overlooked factors could significantly impact the final design.

In terms of power supplies, two were required: one for the 100 V DC and another for the lower voltage. There are no voltage regulators that can step down such high voltages to the required voltage of 24 V DC or 12 V DC. This then led to choosing a 24 V DC power supply. Upon constructing the perforated board prototype, it was found that the voltage regulator was generating too much heat even with a heat sink. It was thought that simply opting for a 12 V power supply could fix this. While the regulator could handle the voltage and heat and maintain linear behavior, reducing the heat generation is crucial when designing the PCB. This is particularly important because the vacuum tubes themselves generate significant heat, and minimizing heat from other components reduces the overall thermal stress on the board. Additionally, this approach provides more design flexibility, allowing the designer to physically separate the heat-generating components from the rest of the circuit. Vacuum tubes already demand separation from the rest of the components on the board as the envelope can reach temperatures up to 110 °C.

Before discussing the assembly of the prototype in the laboratory, it's important to list the components used in this prototype. For the first stage of the pre-amplifier, we used: 1x N-JFET 2SJ112 [28]; 2x 1 μ F 100 V ceramic capacitor and 1x 330 Ω 0.6 W resistor. The second stage utilizes 1x ECC83 double triode valve [12]; 6x 62 k Ω resistors and 2x 1 μ F 100 V ceramic capacitor. The current mirror was constructed using 2x 2N3904 NPN bipolar junction transistors [35]; 1x 10 k Ω 0.2 W resistor; 2x 100 Ω 0.6 W resistor; 1x 330 Ω 0.6 W resistor and 1x 1 μ F 100 V ceramic capacitor. The final stage included 2x 2N3904 NPN bipolar junction transistors [35]; 2x 1 μ F 100 V ceramic capacitors; 3x 10 k Ω resistors.

The full circuit that was implemented is shown in Figure 4.1. However, because this was an early prototype, certain component values and configurations were later adjusted. For example, resistors were added to the emitters of the NPN bipolar transistors in the current mirror at a later stage of the project. The final version of the circuit will be presented with the PCB prototype, which represents the completed hybrid hi-fi audio pre-amplifier design.

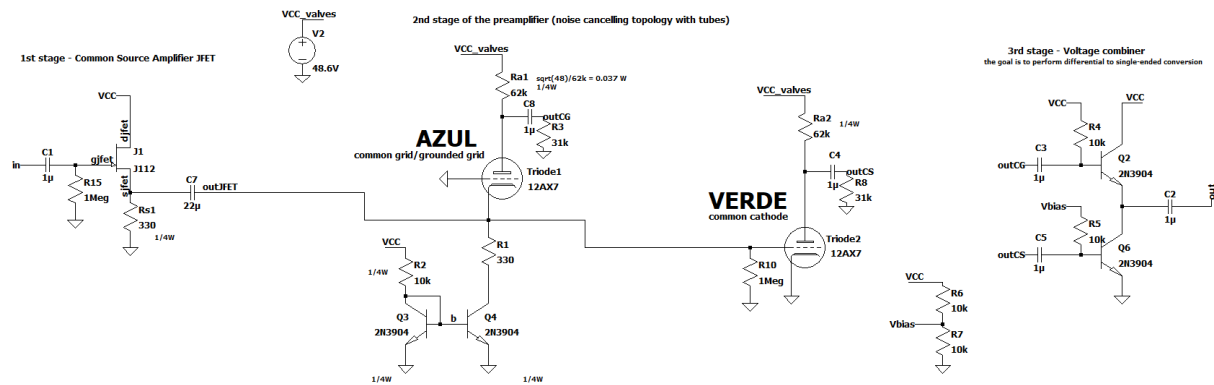


Figure 4.1 - Perforated board circuit.

Perforated Board Results:

The practical development of the prototype involved soldering the first stage to the perforated board. The terminals of the 2SJ112 N-JEFT are slightly different to the conventional drain (1), gate (2) and source (3). To power the solid-state device, we used an adjustable power supply adjusting the supply to 9 V. The input signal was generated by the function generator corresponding to a sinusoidal wave with an amplitude of about 200 mV and a frequency of 1 kHz.

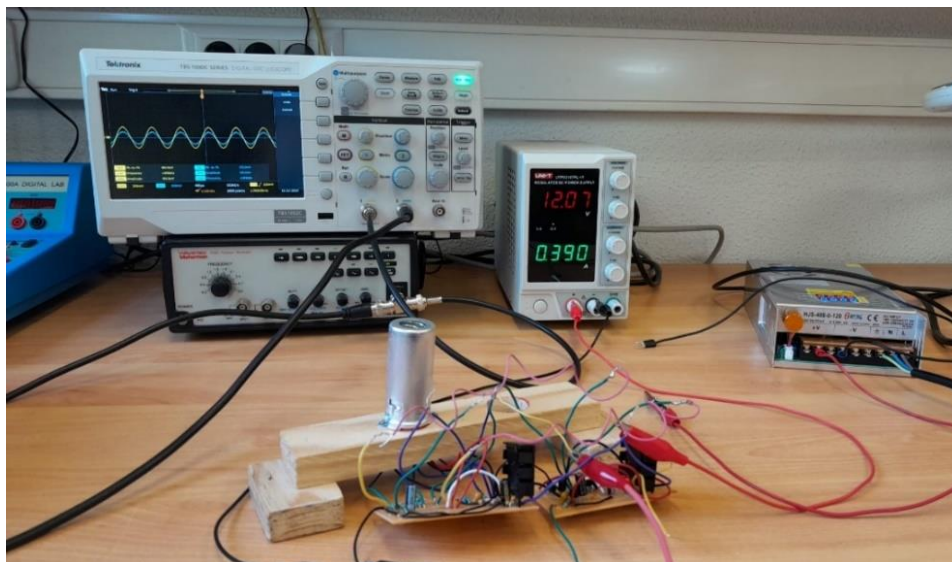


Figure 4.2 - Implementing and testing the first stage of the pre-amplifier.

In Figure 4.2, we can observe the current consumed by the first stage corresponds to 0.014 A or 14 mA. The blue line, corresponding to the second channel of the oscilloscope, corresponds to the input signal generated. The yellow line corresponds to the output of the first stage. There is an attenuation of the input signal, as expected. The input signal has a peak-to-

peak voltage of 480 mV, and the output signal has a peak-to-peak voltage of 274 mV. Dividing the output peak-to-peak voltage by the input peak-to-peak voltage we obtain a value of about 0.6 V/V. The voltage gain obtained in the *LTspice* simulation corresponds to 0.8 V/V. Note that Figure 4.3, corresponds to a version of the first stage that has an electrolytic coupling capacitor with the value of 22 μ F. This value was later adjusted to improve the AC response.

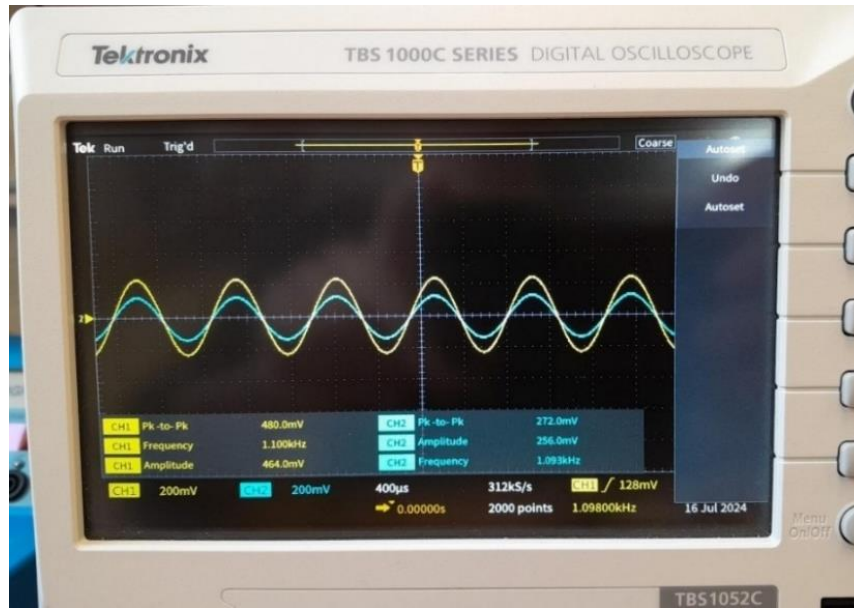


Figure 4.3 - Results of the first stage the input signal, in blue, the output signal, in yellow.

This concludes the work done regarding the first stage of the perforated board prototype pre-amplifier. The next step implies soldering and assembling the second stage. This stage corresponds to the grounded grid and common cathode structure, implemented using vacuum tubes. he selected valve for this stage is the ECC83 double triode valve, also commonly referred to as the 12AX7.

The second stage required the most attention in the prototype due to the numerous connections that had to be added at once. Since this stage incorporates the vacuum tubes, the initial step was soldering all the necessary wires to connect the ECC83 valve from the custom wooden support to the perforated board.

In Figure 4.4, we can observe the output of the grounded grid structure for an input signal of 400 mV peak-to-peak, in yellow. In blue, the output signal of this stage corresponds to 7.7 V peak-to-peak. This corresponds to a voltage gain of 19 V/V or 25 dB. Note that the input signal in being fed only to the second stage in this case. When both stages are joined, an attenuation of the output signal is expected due to the voltage buffer.

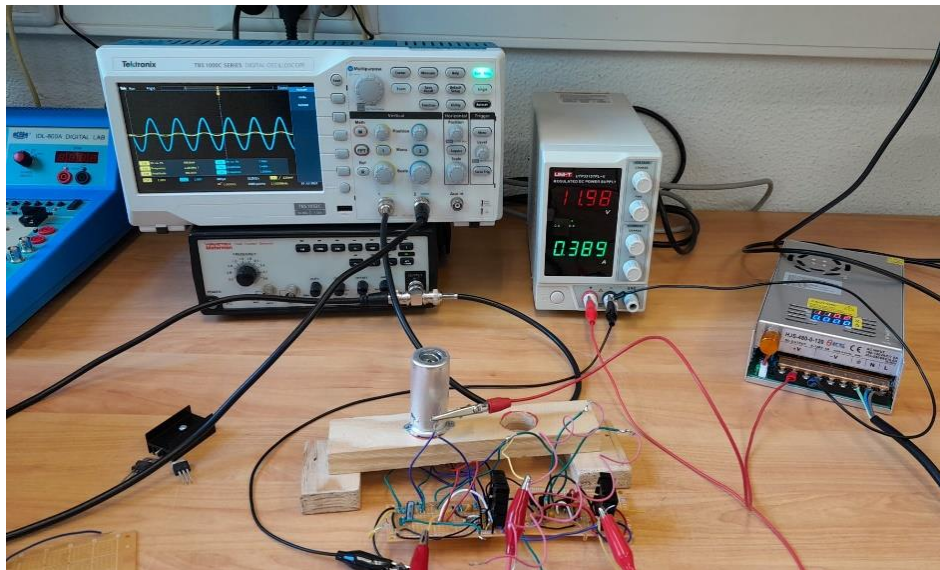


Figure 4.4 – Output of the Grounded Grid with an input signal of 400 mV peak-to-peak and output signal of about 7.7 V peak-to-peak, supply voltage with 110 V.

In Figure 4.5, we can observe the output of the common cathode structure for an input signal of 400 mV peak-to-peak, in yellow. In blue, the output signal of this stage corresponds to 7.5 V peak-to-peak. This corresponds to a voltage gain of 19 V/V or 25 dB. Note that the input signal in being fed only to the second stage in this case. When both stages are joined, an attenuation of the output signal is expected due to the voltage buffer.

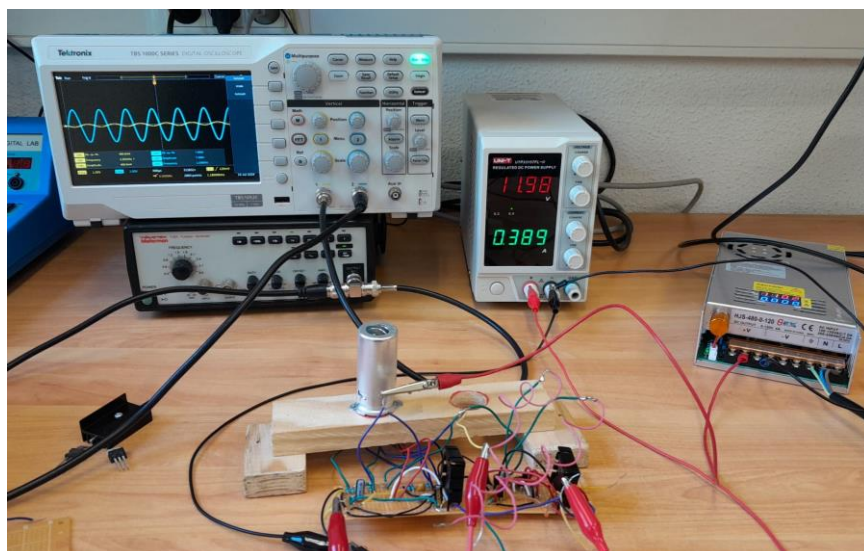


Figure 4.5 - Output of the Common Cathode with an input signal of 400 mV peak-to-peak and output signal of about 7.5 V peak-to-peak, supply voltage with 110 V.

We were able to obtain a very similar gain for both the grounded grid and common cathode structures, meeting one of the key requirements for partial noise and distortion cancelation. Another requirement is that both signals should have opposing phases which can be observed in Figure 4.4 and Figure 4.5. The final step involves summing the two signals using the voltage combiner topology.

While implementing this stage, it was found that the adjustable voltage regulator LM317T has heating up significantly due to being supplied with 24 V DC. To overcome this, we decided to switch the secondary power supply from 24 V DC to 12 V DC. Further issues were found when the LM317T, although producing the correct voltage in the *LTspice* simulation, failed to deliver the expected output voltage when physically implemented. It was found, by examining the datasheet of the component more closely that the minimum working voltage for the LM317T wasn't being met. The voltage divider that should be implement should include one resistor in the order of the 200 to 300 Ω to ensure that this minimum current flows in the component. Once this adjustment was made, the supplied voltage to the filament of the valves corresponded to the expected 6.3 V.

A key challenge of this stage was understanding how to power the valve filaments. According to the ECC83 valve datasheet[12], the double triode valve can be powered with 12.6V at 150mA in series or 6.3 V at 300 mA in parallel. To better understand this, in Figure 4.6 provides a bottom view of the ECC83 valve pins. Pins 4 and 5 correspond to the heaters of the filaments for each triode. Pin 9 corresponds to what's referred to as the "center tap". If powering the valves in parallel, as was done, pins 4 and 5 are connected to the output of the voltage regulator LM317T which should have an output voltage of 6.3 V and pin 9 should be connected to ground. The voltage regulator LM317T can supply up to 1.5 A of current so the needed current for the heater is also supplied.

12AX7-A

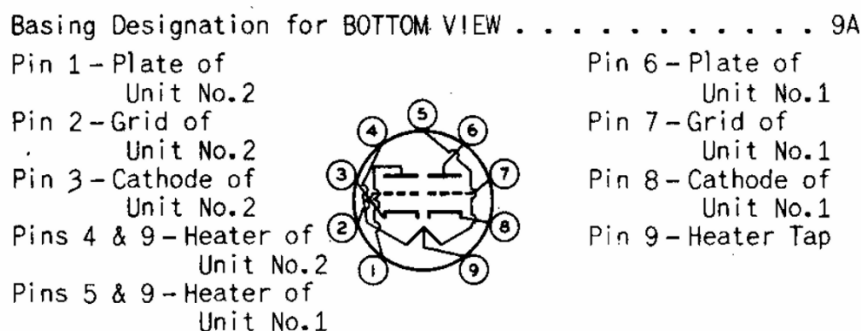


Figure 4.6 - ECC83 bottom view valve pinout (adapted from [13]).

Regarding the voltage combiner topology, the final stage of this pre-amplifier, it is comprised of two 2N3904 NPN bipolar junction transistors and simple resistors need for their biasing. Many values were tested for the voltage combiner as far as *LTspice* simulations go, we chose to implement the voltage combiner using 10 k Ω resistors as can be seen in Figure 4.7.

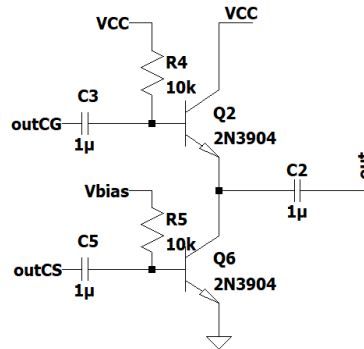


Figure 4.7 - Voltage Combiner circuit implemented in the perforated board prototype.

In Figure 4.9 and Figure 4.11, we can observe some results of all the stages of the pre-amplifier connected. The input signal corresponds to a sinusoidal signal with an amplitude of 400 mV peak-to-peak voltage. Note that the voltage supplied to the valves in this case corresponds to 48.9 V. In Figure 4.8 we can observe the *LTspice* result that was obtained and it will be possible to verify that the results of the simulation versus the perforated board are similar.

In red, we can observe the output of the Grounded Grid configuration being fed to the emitter follower structure of the voltage combiner. In blue, is the output of the common cathode structure being fed to the common emitter configuration of the voltage combiner.

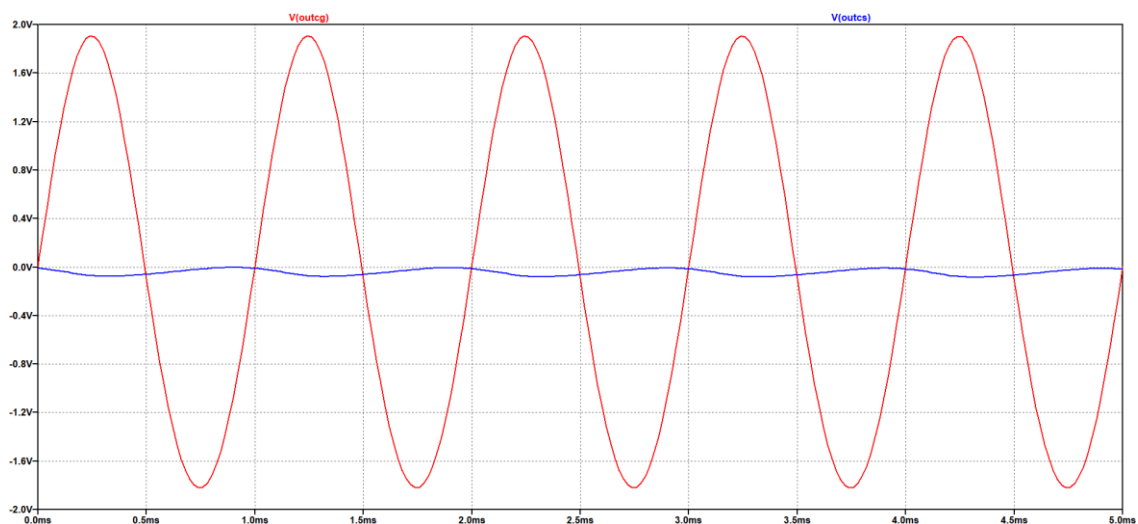


Figure 4.8 - Voltage combiner of the perforated board in *LTspice*.

In Figure 4.9, the output corresponds to the signal that goes from the grounded grid into the emitter follower structure of the voltage combiner. In Figure 4.10, we can observe the result of the oscilloscope more closely. The input signal, in yellow, is fed at the input of the first stage of the pre-amplifier and the output stage, in blue, corresponds to the input of the emitter follower structure of the voltage combiner.

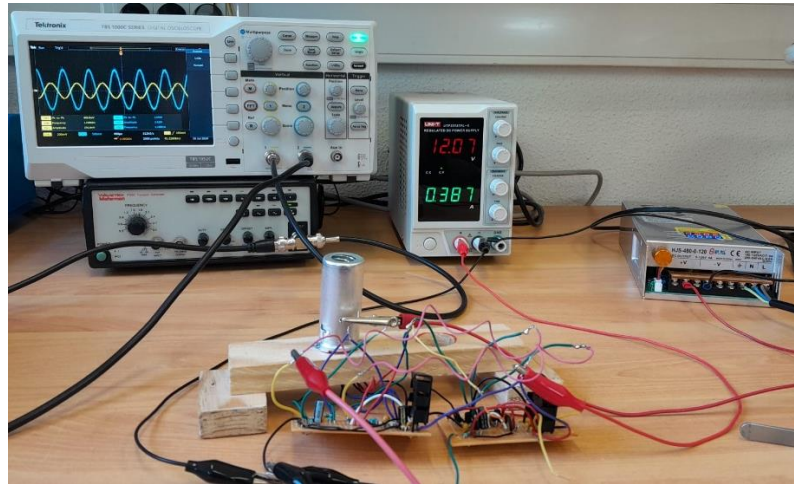


Figure 4.9 - Grounded grid output with all the stages connected between them and valves supplied with 48.6 V.

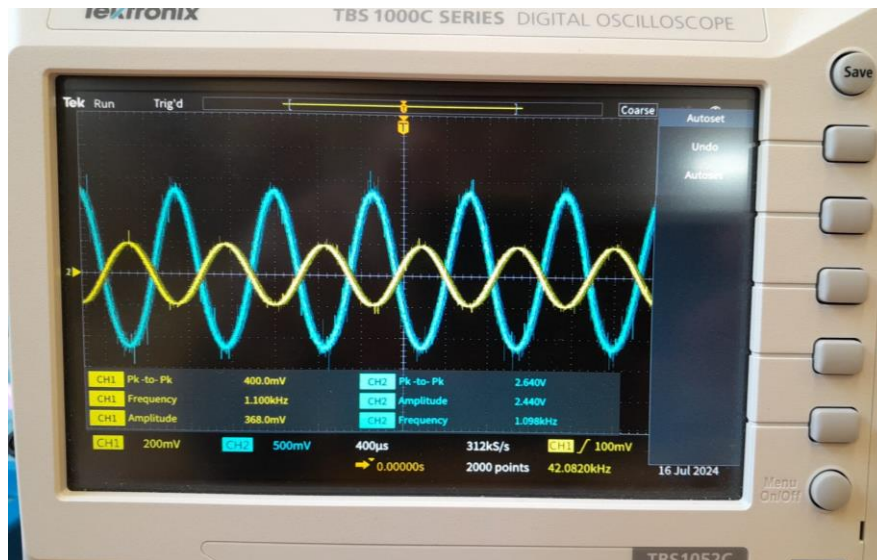


Figure 4.10 – Result obtained from the Grounded grid output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 2.64 V peak-to-peak.

In Figure 4.11, output corresponds to the signal that goes from the common cathode into the common emitter structure of the voltage combiner. In Figure 4.12, we can observe the result of the oscilloscope more closely. The input signal, in yellow, is fed at the input of the first stage of the pre-amplifier and the output stage, in blue, corresponds to the input of the

common emitter structure of the voltage combiner. We can observe a significant reduction of the signal. This result is in accordance with the *LTspice* simulations that can be done for this stage.

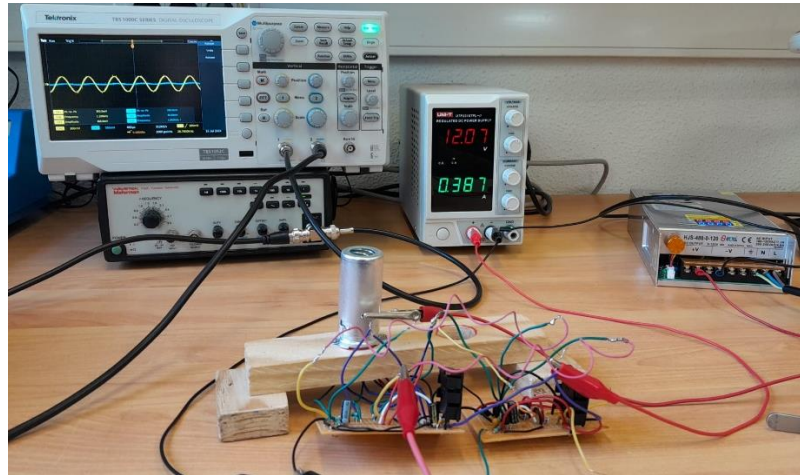


Figure 4.11 - Common cathode output with all the stages connected between them and valves supplied with 48.6 V.

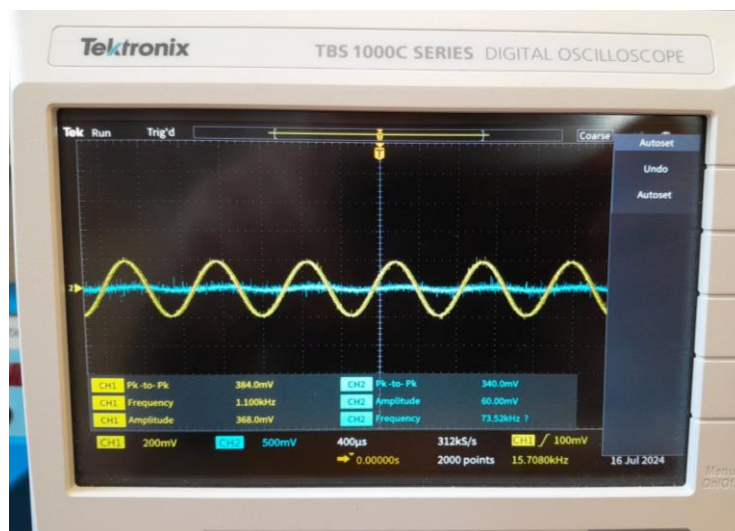


Figure 4.12 - Result obtained from the Common cathode output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 343 mV peak-to-peak.

To finalize this subsection on the perforated board prototype of the hybrid hi-fi audio pre-amplifier using transistors and vacuum tubes, we show the result of the three stages of the pre-amplifier. Note that the valves, in this case, were supplied with 48 V. In Figure 4.14, we can observe the output of the pre-amplifier, in blue, which corresponds to a 2.8 V peak-to-peak sinusoidal signal. The input signal, in yellow, corresponds to a sinusoidal signal with an amplitude of 400 mV peak-to-peak. This means that, the perforated board prototype has a voltage gain of 7 V/V, or 17 dB which is a little below the expected 20 dB. Additionally, in Figure 4.13,

we can observe that the circuit is consuming 387 mA of current, which means that we can simply use one 9 V voltage regulator to supply the stereo version of the design as the L7809CV can supply up to 1.5 A of current if needed.

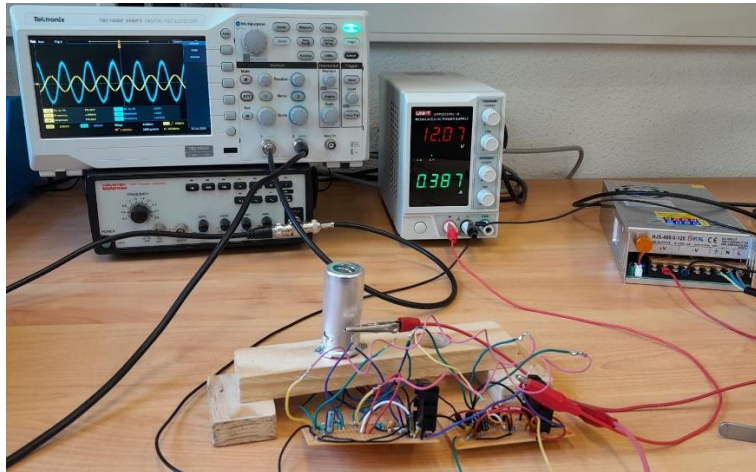


Figure 4.13 - Perforated board pre-amplifier prototype output with all the stages connected between them and valves supplied with 48.6 V.

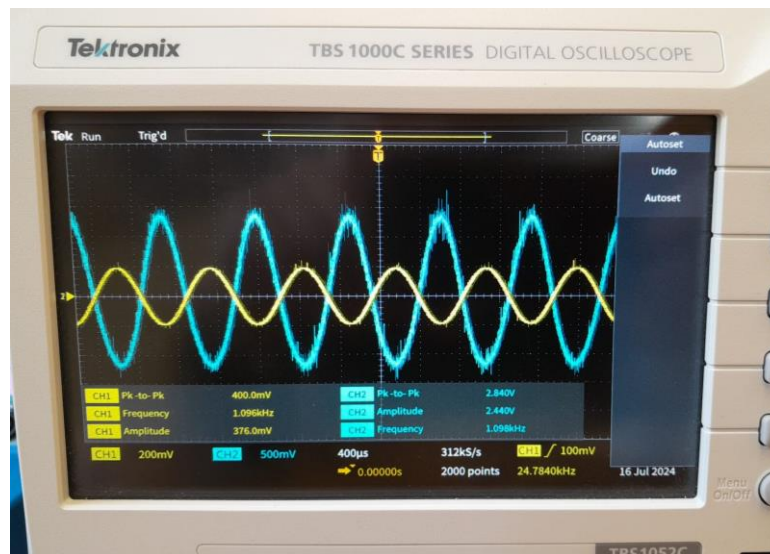


Figure 4.14 - Result obtained from the perforated board pre-amplifier prototype output with all the stages connected between them. The input signal, in yellow, has 400 mV peak-to-peak; the output signal, in blue, has 2.84 V peak-to-peak.

This perforated board prototype was built as a learning platform. It allowed for some crucial modifications, namely, employing the corrections to the biasing circuit of the LM317T adjustable voltage regulator which supplies the necessary power to the filament of the valves. Due to the poor built quality, measurements of noise and total harmonic distortion were not

conducted. The next subsection will focus on the printed circuit board prototypes, providing a more comprehensive evaluation of the pre-amplifier's performance aspects.

4.2 Printed Circuit Board Prototype

This subsection focuses on the printed circuit board (PCB) prototype of the hybrid hi-fi audio pre-amplifier. This is the most significant prototype as it consolidates the physical considerations that were learned from implementing and testing the perforated board prototype. Through building the previous prototype, we optimized the PCB layout to provide more space for heat-generating components, such as the vacuum tubes and the LM317T adjustable voltage regulator.

Two PCB versions were developed using *KiCad* version 8.0. *KiCad*, an open source software for developing printed circuit boards. *KiCad* allows for the use of extensive libraries of footprints and symbols and offers tools like the 'Footprint Editor' and 'Symbol Editor' to create custom footprints and symbols, respectively. One of *KiCAD*'s useful features enables the designer to upload a .spice schematic, edit it in the 'Schematic Editor' and update the PCB from the schematic having the modifications reflected in the board layout. Additionally, the software's 3D viewer is helpful in preventing overlapping components or incorrect trace routing.

The first PCB version was a learning experience. The second PCB prototype serves as acknowledgement that further modifications can be done to the prototype and therefore improve the performance of the pre-amplifier. The development of these boards was made possible through the guidance of Professor João Pedro Oliveira, who provided valuable input on PCB design. The PCB pre-amplifier is a four-layer board, with the following structure:

- TOP layer: component layer, signal routing primarily.
- SECOND layer: GND layer, ground plane.
- THIRD layer: 9V layer, power plane only.
- BOTTOM layer: 100V layer, power plane and some signal routing.

The four-layer board simplifies the designer's task of having to conciliate signal and power routing by shifting the focus primarily to the signal routing. Surface Mount Devices (SMD) that are on the top layer and need to be powered with 9 V DC, for example, can be connected by simply connecting the pad of the component to the via that connects the top and 9 V planes. The connections from component and ground (GND) planes are done in the same manner. From the component, a short trace and via are placed, connecting the component from the top layer to the GND layer.

Being an audio application and a pre-amplifier which should be stereo, symmetry of the design is crucial. Furthermore, to reduce noise, heat-generating components are placed, as much as possible, far away from other elements on the board. To achieve this, some traces will have to be longer. Ideally, trace length should be short to minimize crosstalk, coupling and reflections. In this case, a compromise must be found, as the noise of the pre-amplifier could increase significantly if not taking this into consideration. These are some of the first concerns that arise when starting to design a printed circuit board prototype.

This subsection will explore into all the design considerations that were had for both PCB versions. Performance aspects of the PCB prototype for version 1 will be featured in this subsection. Due to time constraints, only version 1 of the PCB prototype pre-amplifier was ordered, built, soldered and tested. Version 2 should incorporate further improvements and enhance performance in future iterations. It serves to acknowledge not only the work that was put into version 1 of the prototype but recognize as well, that there's potential to further improve the results.

4.2.1 PCB Prototype Version 1

This subsection addresses the first version of the PCB prototype. The circuit corresponding to this board is shown in Figure 4.15. Note that, this version of the pre-amplifier will be stereo, meaning that we simply replicated the board two times in order to deal with the left (L) and Right (R) audio signals that will be fed into the design. The values of the components are the same for both left and right sides. The only non-symmetrical portion of the design relates to power supply requirements, where one 9 V DC voltage regulator is needed to power the entire board, based on insights gain from the perforated board prototype development.

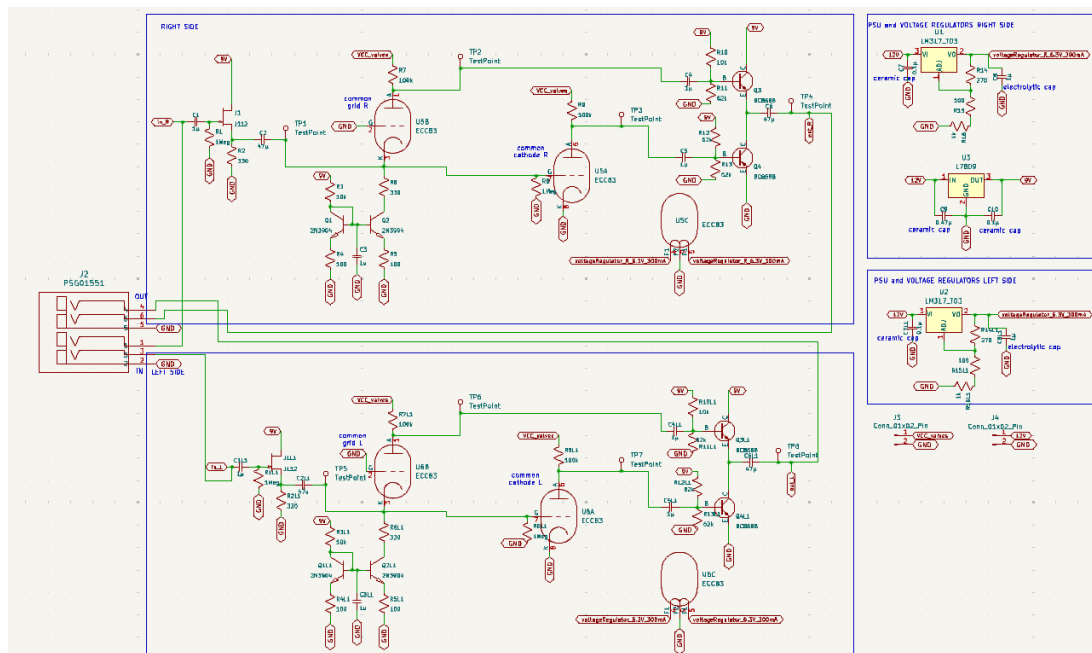


Figure 4.15 - PCB prototype Version 1 Circuit.

The design process began by uploading the .spice schematic into *KiCad's* "Schematic Editor". The circuit was duplicated to create left and right channels, essential for the stereo configuration of the pre-amplifier. One of the first tasks was selecting a suitable symbol and footprint for the RCA connectors used for both input and output signals. The chosen RCA model included computer-aided design (CAD) models that were imported into *KiCad*. In the schematic present in Figure 4.15, component 'J2' represents the RCA connectors.

Regarding the valve connections, the schematic might appear to show three triodes per channel; however, this is only a schematic symbol in *KiCad* to represent additional connections needed for the heater of the ECC83/12AX7 valves. Furthermore, components 'J3' and 'J4' in Figure 4.15 are terminals for the 100 V DC and 12 V DC power supplies.

Further modifications that are contemplated in this version of the PCB prototype correspond to the adjustment of the biasing network of the LM317T, the adjustable voltage regulator so that the component itself has the minimum current to function properly.

During the board design process, extensive research was conducted to understand critical concepts such as minimum trace width, clearance, and via diameter. These parameters vary depending on the specific application and the capabilities of the PCB manufacturer. Additionally, other important layers, like the 'Solder Mask' and 'Silkscreen' layers, required further investigation to fully grasp their purpose and relevance in the design. Finally, one important concept has to do with copper pours, when to use them, how to do execute them in *KiCad*.

At this stage, a bill of materials (BOM) was created to determine the required footprints for all components. Each component was meticulously selected, ensuring that surface-mount devices (SMDs) were primarily of the 1206 metric size, making them easier to solder. For through-hole electrolytic capacitors, careful consideration was given to choosing components with the appropriate lifetime and voltage ratings. Similarly, through-hole versions of voltage regulators were selected to ensure better connections across the power planes.

An important part of component selection was verifying that each component had a compatible *footprint* available in *KiCad*. On some occasions, it was found that the manufacturers had not developed an open-source CAD model, custom *footprints* were created with the help of the *datasheet* of the component, which provides the exact sizing information.

After carefully selecting all the components, the next step in the *KiCad* project was to manually verify that all the *footprints* of the components match the ones of the PCB design. Regarding electrolytic capacitors, their *datasheets* were consulted and based on the voltage rating and capacitance value, their dimensions are specified. The designer must then make sure that the *footprint* in the *KiCad* matches that of the *datasheet*. For SMD resistances and ceramic capacitors the process is much simpler. The designer must make sure that the *footprint* corresponds to the SMD size of the components. Most of the components were chosen to be of the 1206 (3216 metric) size, which is a big enough size, in terms of SMD components, to be soldered by hand.

The next step in designing the printed circuit board involves layout. At this point, we've set the minimum trace widths and clearances and via sizes with our board, making sure that it doesn't exceed manufacturer's capabilities, chosen the components that will be used and verified all their *footprints* match both in *KiCad* as with their *datasheets*. This is a board with analog components only and so the designer's task of performing the layout becomes rather trivial. The goal is to minimize the size of the board, due to costs, and making sure that the appropriate components are further placed from the rest of the board. Such is the case for heat-generating components such as vacuum tubes as well as voltage regulators.

Several iterations of the layout were made before reaching the design shown in Figure 4.16. With the help of professor João Pedro Oliveira, adjustments were made by repositioning certain components to shorten some of the trace lengths. It was recommended that the voltage regulators have a through-hole packaging to help ensure proper electrical connections between the ground and component planes.

The final layout manages to have the first and third stages as well as the bipolar transistor current mirror in a reduced area of the printed circuit board. However, the second stage is where the problems arise. Trace lengths should be minimized as to make sure that electromagnetic interference is at a minimum. Additionally, components like voltage regulators and

thermionic valves generate substantial heat, necessitating their separation from other components to prevent thermal issues.

After achieving an acceptable layout, the next step in the PCB design process involves connecting all the components using traces and vias. For components in the same layer and in close proximity, the trace should be kept as short and direct as possible. For components that require a ground or any other power connection (such as 9 V or 100 V) the designer must draw a short trace and place a via close to the component's pad. A via is to a drilled hole that allows connections between different PCB layers. For components that are further apart, the trace must be longer, but the overall benefits are greater by separating such components. In some cases, signal routing was optimized by utilizing the 100 V plane to create more direct traces. For surface-mounted components on the top layer, a short trace is drawn, a via placed nearby and in the 100V the designer connects the via to the desired component.

In Figure 4.16, shows the final design with all the layers and respective copper pours visible, on layers two (GND layer) and three (9 V layer). This is the result achieved for the design of the printed circuit board prototype done in the open source *software KiCad*. The next step involves sending the design for production and assembly. Figure 4.17 and Figure 4.18 allow for the designer to observe the 3D view of the developed product. The results achieved with this prototype will be present in the next subsection.

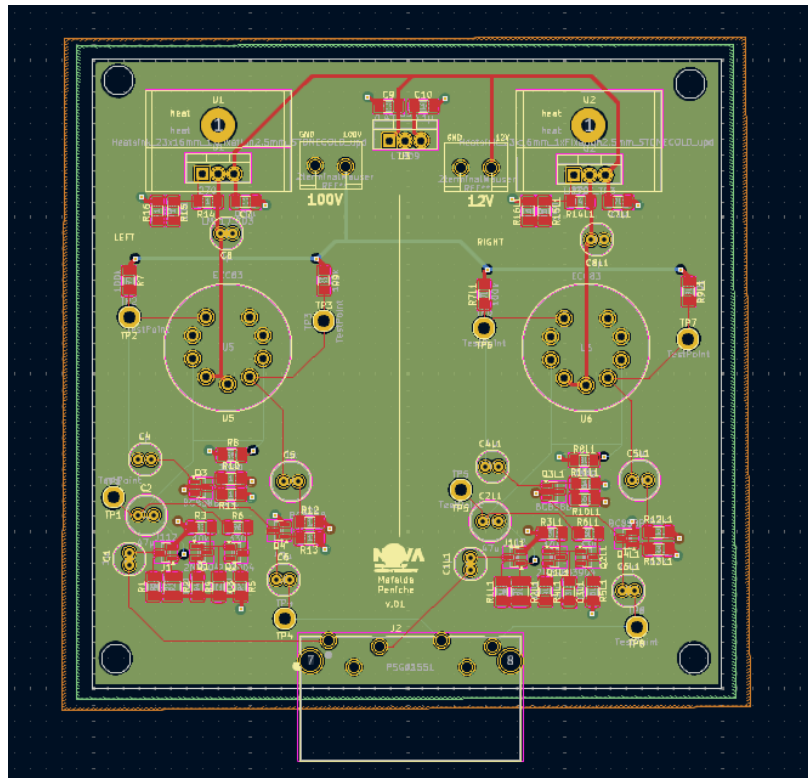


Figure 4.16 - Front view of the printed circuit board prototype Version 1 in *KiCad*.

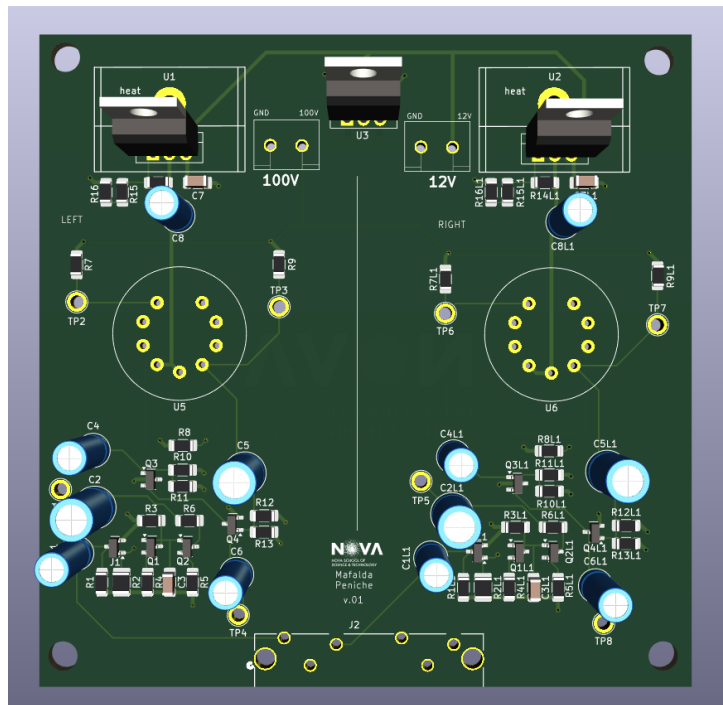


Figure 4.17 – Front 3D view of printed circuit board prototype Version 1 in *KiCad*.

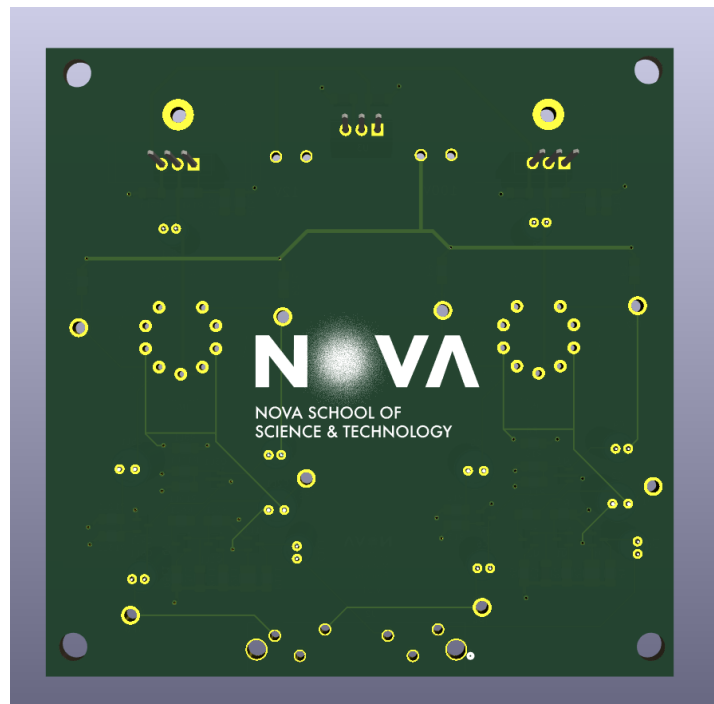


Figure 4.18 - Back 3D view of printed circuit board prototype Version 1 in *KiCad*.

When returned from the production line, the board look corresponds to the expected. The next step consists of soldering the SMD components to their respective places and power the printed circuit board, verifying it works. In Figure 4.19, the result of all the soldering and assembling of the PCB is shown.



Figure 4.19 - Assembled hybrid hi-fi audio pre-amplifier PCB version 1.

In Figure 4.20 we can observe the laboratory setup to verify that the printed circuit board is working. For one, we must feed a stereo audio signal in the two vertical RCA connectors to the left. Additionally, an RCA cable must be connected from the two vertical RCA connectors to the right to the oscilloscope or a power amplifier (or audio interface) and then fed to some power amplification (PA) system to hear the result. After connecting the pre-amplifier to the audio interface and some speakers we verified that the pre-amplifier is working as expected. When not playing any audio signal and with the sound at a considerable volume, we hear no hissing sound which can be taken as an indication that the pre-amplifier has low noise as intended.



Figure 4.20 - Laboratory setup to test audio pre-amplifier PCB prototype version 1.

By feeding a 232 mV peak to peak input signal (in blue), as shown in Figure 4.21, we can observe that the output signal has a 2.68 V peak to peak signal (in yellow), which results in a gain of 11.65 V/V or 21.3 dB. The intended gain of the pre-amplifier was given as 20 dB, meaning that this requisite was achieved. Regarding noise, a simple comparison between Figure 4.14 and Figure 4.21 shows that the result of the PCB prototype has very little noise. However, true measurements of the audio pre-amplifier noise will be obtained with the ATS-2 Audio Precision equipment.

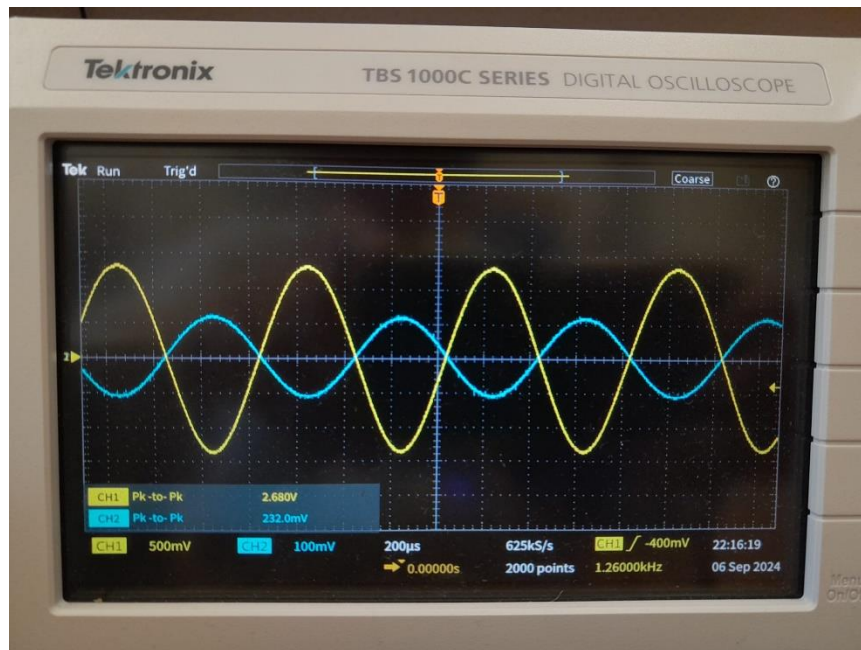


Figure 4.21 - Result of audio pre-amplifier PCB prototype version 1.

The next step in this work involves using the ATS-2 Audio Precision equipment to assess the performance of the hybrid hi-fi audio pre-amplifier. It is only when testing the prototype with this equipment that we can truly measure the final performance aspects.

4.2.2 Results with ATS-2 Audio Precision

The performance aspects we want to measure include total harmonic distortion, nominal gain, noise figure, input and output impedances, and bandwidth. Regarding specifications, the audio pre-amplifier should have a gain of about 10 V/V or 20 dB while achieving low noise and THD. The reference value for low noise and distortion (THD+N) should be between one and two percent (1 %- 2 %) [2], [3], [4].

The nominal gain value has been achieved since in the last subsection the gain was measured at 11.65 V/V or 21.3 dB. The input impedance has a value of about 1 M Ω while the output impedance has a value of 1 k Ω .

It is important to note that the bandwidth of the amplifier is greater than 20 kHz although the ATS-2 Audio Precision only performs the frequency response sweep from 20 Hz to 20 kHz. In Figure 4.22, we can observe the ATS-2 Audio Precision equipment used to perform the frequency response and distortion and noise (THD+N).



Figure 4.22 - ATS-2 Audio Precision equipment.

Additional equipment needed to replicate these tests include a male RCA stereo to male XLR cable and a male RCA stereo to female XLR stereo cable. These allow for the connection of the “Analog Output” of the ATS-2 equipment to the RCA input of the pre-amplifier and for the connection of the output of the pre-amplifier to the “Analog Input” of the ATS-2 equipment, as shown in Figure 4.23.

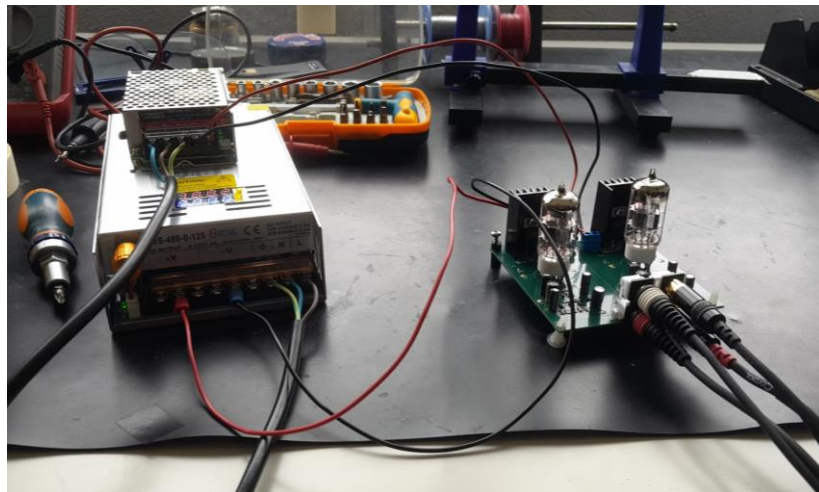


Figure 4.23 - Laboratory setup for measuring TDH+N and frequency response of the PCB prototype version 1 pre-amplifier.

Using the “Analog Generator” function of the ATS-2 Audio Precision we are able to generate a sinusoidal signal with an amplitude of 100 mV peak to peak and a frequency of 1 kHz and feed that signal to the pre-amplifier. The ATS-2 is able to characterize the pre-amplifier by

measuring the differences of the output signal of the pre-amplifier with the input signal that it generated.

First, the frequency response test was performed. The settings of the test are shown in Figure 4.24 where the input signal fed to the pre-amplifier is a sinusoidal signal with an amplitude of 100 mV peak to peak and 1 kHz frequency by the “Analog Generator” function. In the “Analog Input” function we can observe the amplitudes of the stereo (left + right) output signal from the pre-amplifier.

In the “Sweep” window, we can choose the number of steps of the simulation, the Start and Stop frequencies and a Stereo or Mono (default) sweep. Because the developed pre-amplifier has a left and right side, the test should be Stereo to include both sides. It explains the blue and green lines that appear on the graph shown in Figure 4.25.

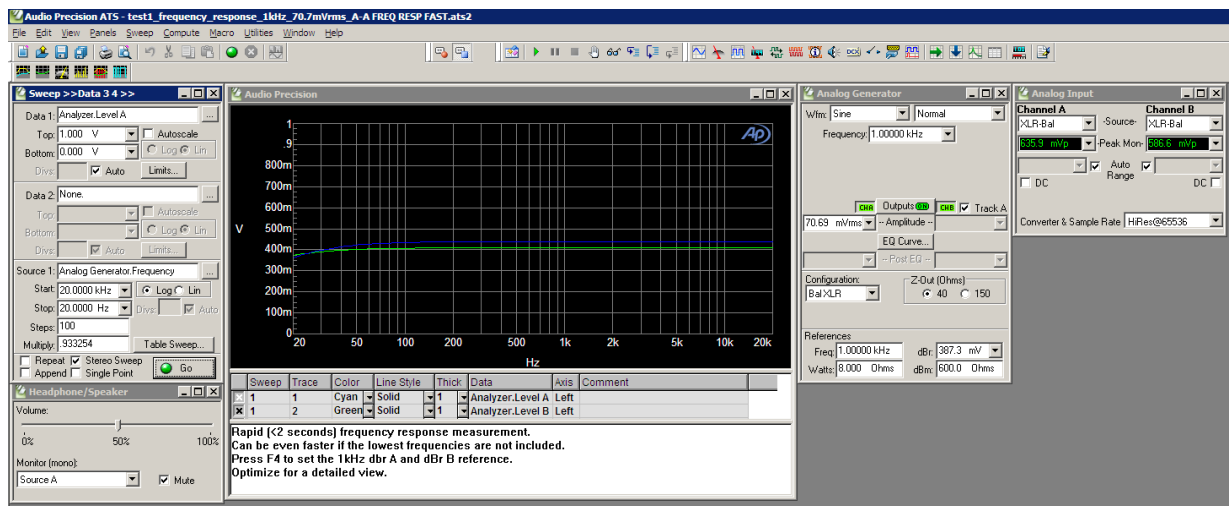


Figure 4.24 - Settings of ATS-2 for frequency response test.

In Figure 4.25, we can observe the result of the frequency response test with the ATS-2 Audio Precision equipment. As mentioned previously, the frequency response of audio equipment should be flat [2], [3], [4]. Visually, it means that the result obtained with any of this type should roughly be a horizontal line across the 20 Hz to 20 kHz frequencies.

The result obtained for the PCB prototype version 1 of the pre-amplifier can be characterized as flat. There's a slight amplitude reduction in the lower frequencies (between 20 Hz and 50 Hz) which is certainly not audible even for more experienced listeners.

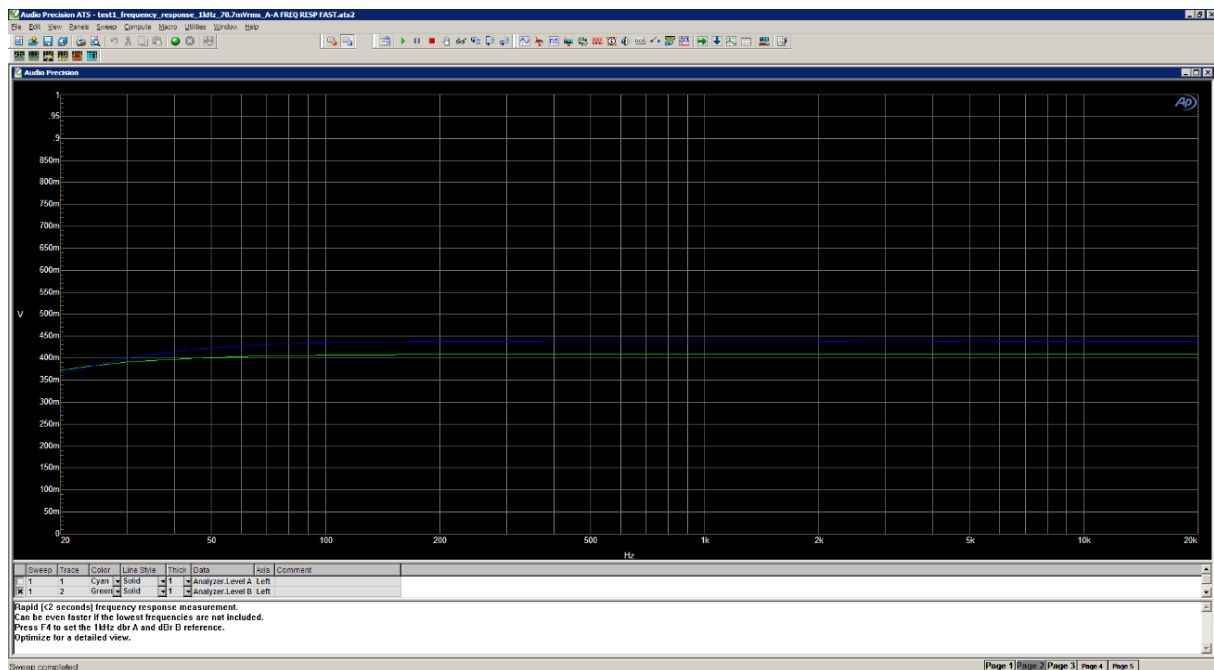


Figure 4.25 - Result of the frequency response test with ATS-2 Audio Precision.

Second, the distortion and noise (THD + N) test was performed. The settings of the test are shown in Figure 4.26 where the input signal fed to the pre-amplifier is a sinusoidal signal with an amplitude of 50 mV peak to peak and 1 kHz frequency by the “Analog Generator” function. In the “Analog Input” function we can observe the amplitudes of the stereo output signal from the pre-amplifier. In the “Sweep” window, we can choose the number of steps of the simulation, the Start and Stop frequencies and a Stereo or Mono (default) sweep. The test should be Stereo to include both sides of the pre-amplifier.

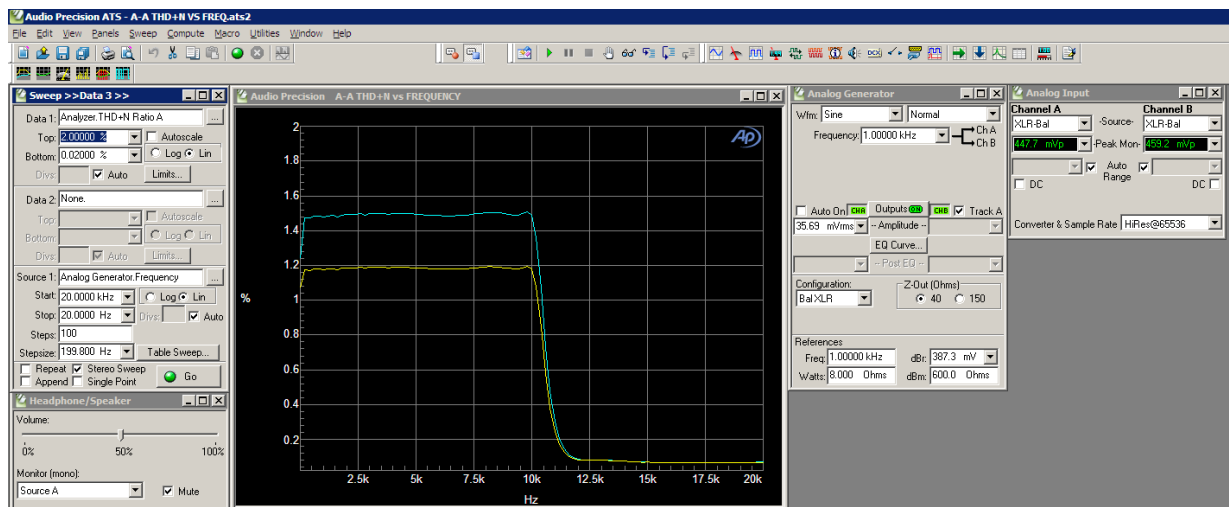


Figure 4.26 - Settings of ATS-2 for distortion and noise (THD+N) test.

In Figure 4.27, we can observe the result of the distortion and noise (THD + N) test with the ATS-2 Audio Precision equipment. The ideal value for total harmonic distortion in audio equipment should be below 1% [34], [35].

The result obtained for the PCB prototype version 1 of the pre-amplifier can be characterized as low noise and with an acceptable value of total harmonic distortion. It is important to note that the sweep performed by the ATS-2 Audio Precision equipment only measures the noise above 10 kHz. We can then characterize the noise of the pre-amplifier as 0.1%. Note also that at 6 kHz only the 2nd and 3rd harmonics are included. The measured distortion and noise (TDH+N) values are 1.2% and 1.5%.

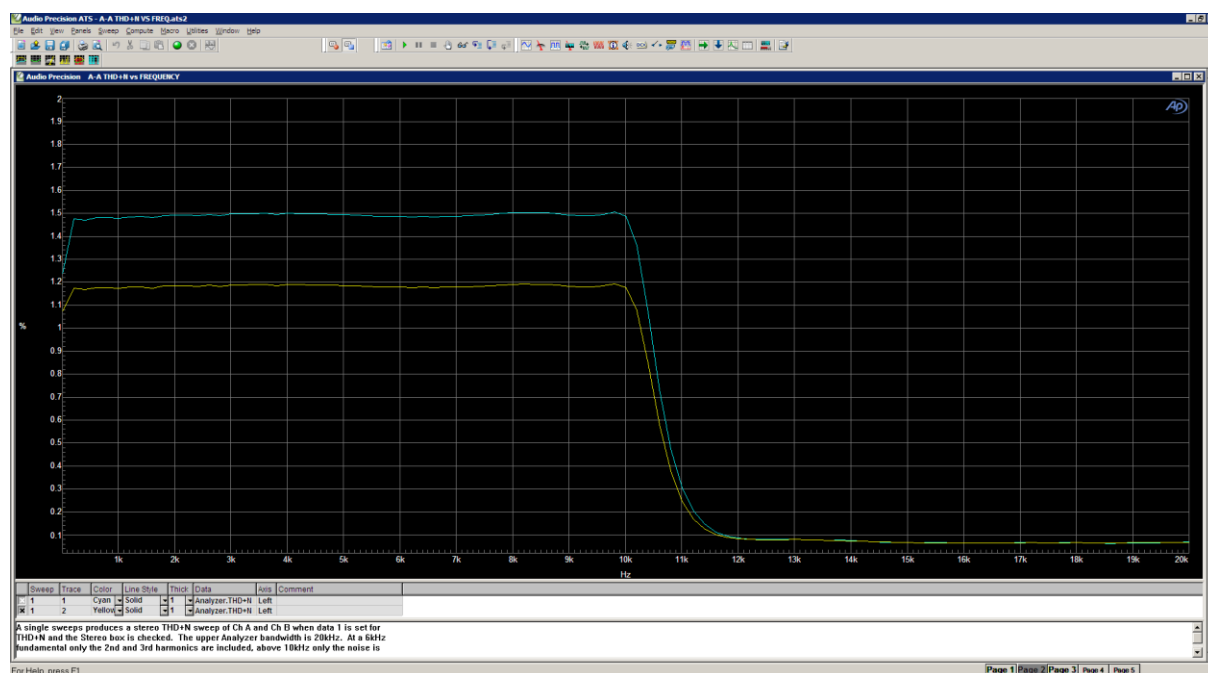


Figure 4.27 - Result of the distortion and noise (THD+N) test with ATS-2 Audio Precision.

It is important to state that to obtain the best results in terms of total harmonic distortion of the pre-amplifier, the intrinsic parameters of the vacuum tubes such as transconductance (g_m), anode internal resistance (r_p) and amplification factor (μ) must be matched. This is due to matching errors influencing the performance of these devices significantly. To minimize these errors and ensure the best performance of the pre-amplifier, vacuum tubes must be matched.

This concludes the measurement of performance aspects of the PCB prototype version 1 pre-amplifier where we observed a gain of 11.65 V/V or 21.3 dB, a flat frequency response and a distortion and noise (TDH+N) of 1.2% and 1.5%.

CONCLUSIONS AND FUTURE WORK PROPOSALS

This work consists of designing and implementing an audio pre-amplifier with a hybrid configuration incorporating transistors and vacuum tubes and utilizing modern practices for noise reduction and cancelation. We set out to achieve the best of two worlds: the pleasant total harmonic distortion (THD) from the vacuum tubes with improved signal-to-noise ratio (SNR).

Regarding original contributions, the use of several types of devices is of importance as it was attempted to employ them in their most advantageous scenarios. Take the junction field effect transistor, which has a high input impedance and has a lower noise figure than the bipolar transistor (in most cases). By employing this kind of device in the crucial first stage of the pre-amplifier as a voltage buffer, the signal fed into the thermionic valves has a lower noise contribution than it would have had, had the bipolar junction transistor been employed. The use of thermionic valves to perform noise-cancelation must be highlighted, as, in researching for this project, no literature or projects were found where this technique was employed. Moreover, while researching for this work, it was found that the distortion produced by vacuum tubes is often perceived as more pleasant due to the predominance of even-order harmonics, justifying their relevance and preference in audio electronics.

The most important research and content found to aid in our efforts of achieving this hybrid hi-fi audio pre-amplifier using modern techniques for noise cancelation is present in Chapter 2. Chapter 3 pertains to the theoretical development of the design. It contains a detailed explanation of each biasing network as well as the workings of structures such as the voltage combiner and the noise-cancelling topology. Chapter 4 corresponds to the practical development of the prototypes starting with the perforated board prototype which was mostly a learning platform and helped aid in the better performance of the printed circuit board prototype.

5.1 Conclusions

The main difficulties with this work have to do with implementing the voltage combiner with bipolar junction transistors. The literature found consisted of implementation of this topology using metal oxide semiconductor field effect transistors (MOSFET). In this case, we chose to implement it with bipolar junction transistor due to their predictable operation and relatively low noise.

The final pre-amplifier prototype made with printed circuit board achieves a gain of 21.3 dB. The performance parameters that were measured include frequency response and total harmonic distortion and noise. Using the ATS-2 Audio Precision it was observed that the final prototype exhibits a flat frequency response, low noise and distortion (1.2% on the left side of the pre-amplifier and 1.5% on the right side).

Concluding the development of this work, it can be said that the main objectives of designing and building a hybrid hi-fi audio pre-amplifier using vacuum tubes to perform noise cancelation were achieved. It was verified, through computer simulations, that the common-gate and common-source noise cancellation topology can be implemented with vacuum tubes and achieve partial noise and distortion cancellation.

5.2 Future Work Proposals

Directly related to this work, in terms of design, one suggestion for the future would be to implement the voltage combiner structure with junction field effect devices. These devices have a higher input impedance than bipolar junction transistors and contribute with less noise. Furthermore, all solid-state devices can be powered with 12V. This would increase the output swing in the voltage combiner structure, reducing the total harmonic distortion of the pre-amplifier.

Regarding the prototypes, it is recommended to design an improved printed circuit board. Whilst the final prototype presented is functioning as expected, there are plenty of aspects of the design that can be further improved. Such aspects correspond to the symmetry of the board, choosing a more adequate *footprint* for the vacuum tube mount and the electrolytic capacitor at the output of the first stage of the pre-amplifier, improve the silkscreen reference values locations of some components, add the polarity silkscreen indication for all electrolytic capacitors, improve trace consistency as well as remove some redundant traces. Regarding improving trace consistency, this pertains to the differing width of some traces connected between different layers by a via. In some instances, a trace is wider on the component layer and on the next layer the trace width changes. This should be fixed to improve the overall design

further. With the improved PCB design, the next step would be to order more of the components and printed circuit boards to develop more of the hybrid hi-fi audio pre-amplifiers.

BIBLIOGRAPHY

- [1] E. Barbour, "The Cool Sound of Tubes," 1998.
- [2] R. O. Hamm, "Tubes Versus Transistors - Is There an Audible Difference?," 1972.
- [3] W. Liu and F. Analog, "HiFi Audio Circuit Design Application Report HiFi Audio Circuit Design," 2017. [Online]. Available: www.ti.com
- [4] D. Self, "An advanced preamplifier design," *Wireless World*, pp. 40–42, Nov. 1976. Accessed: Sep. 20, 2024. [Online]. Available: <https://www.worldradiohistory.com/UK/Wireless-World/70s/Wireless-World-1979-02-S-OCR.pdf>
- [5] D. Self, "A high-performance preamplifier design," *Wireless World*, pp. 40–42, Feb. 1979. Accessed: Sep. 20, 2024. [Online]. Available: <https://www.worldradiohistory.com/UK/Wireless-World/70s/Wireless-World-1979-02-S-OCR.pdf>
- [6] J. L. Hood, "Valve and Transistor Audio Amplifiers," 1997.
- [7] M. Blencowe, "Designing Tube Preamps for Guitar and Bass," 2009.
- [8] RCA, "RCA Receiving Tube Manual," 1968.
- [9] J. Korterik, "Triode common-cathode amplifier calculator." Accessed: Mar. 17, 2024. [Online]. Available: <https://hosenlander.nl/triodecalculator2/index.html>
- [10] Philips, "ECC83 Double High Mu Triode," Nov. 1954.
- [11] N. J. Harrison, "12AX7 High-Mu Twin Triode - Radio Corporation of America: Electron Tube Division," Jul. 1937.
- [12] M. Jones, "Valve Amplifiers," 2003.
- [13] D. Self, *Audio Power Amplifier Design Handbook*. Routledge, 2012. doi: 10.4324/9780080953892.
- [14] Douglas. Self, *Small signal audio design*. Focal Press, 2010.
- [15] W. Schottky, "Small-Shot Effect and Flicker Effect," *Physical Review*, vol. 28, no. 1, pp. 74–103, Jul. 1926, doi: 10.1103/PhysRev.28.74.
- [16] G. L. Pearson, "Fluctuation noise in vacuum tubes," *J Appl Phys*, vol. 5, no. 9, pp. 233–243, 1934, doi: 10.1063/1.1745257.

- [17] W. Shockley and E. M. Field, "Electrons and Holes in Semiconductors," *Phys Today*, vol. 5, no. 12, pp. 18–19, Dec. 1952, doi: 10.1063/1.3067420.
- [18] E. Borbely, "JFETS: The New Frontier, Part 1," *Audio Eletronics*, pp. 5–99.
- [19] F. Bruccoleri, E. A. M. Klumperink, and B. Nauta, *Noise cancelling in Wideband CMOS LNAs*. IEEE, 2002.
- [20] S. C. Blaakmeer, E. A. M. Klumperink, D. M. W. Leenaerts, and B. Nauta, "Wideband balun-LNA with simultaneous output balancing, noise-canceling and distortion-canceling," *IEEE J Solid-State Circuits*, vol. 43, no. 6, pp. 1341–1350, Jun. 2008, doi: 10.1109/JSSC.2008.922736.
- [21] I. Bastos, L. B. Oliveira, J. Goes, and M. Silva, "A low power balun LNA with active loads for gain and noise figure optimization," *Analog Integr Circuits Signal Process*, vol. 81, no. 3, pp. 693–702, Dec. 2014, doi: 10.1007/s10470-014-0426-6.
- [22] J.-P. Fanton and F. Lamonaca, "On the mythic sound of vacuum tubes," 2023. [Online]. Available: www.imeko.org
- [23] R. Póvoa, N. Lourenço, R. Martins, A. Canelas, N. Horta, and J. Goes, "Single-Stage OTA biased by Voltage-Combiners with Enhanced Performance using Current Starving," 2019.
- [24] R. Póvoa, N. Lourenco, N. Horta, and J. Goes, "A voltage combiners biased amplifier with enhanced gain and speed using current starving," in *2015 IEEE International Symposium on Circuits and Systems (ISCAS)*, IEEE, May 2015, pp. 2069–2072. doi: 10.1109/ISCAS.2015.7169085.
- [25] O. Semiconductor, "J111, J112 - JFET Chopper Transistors," Mar. 2006. [Online]. Available: <http://onsemi.com>
- [26] F. George Dalrymple, "A measurement of Resistance Noise," 1954.
- [27] F. B. Llewellyn, "A study of noise in vacuum tubes and attached circuits," *Proceedings of the Institute of radio Engineers*, vol. 18, no. 2, Feb. 1930.
- [28] G. Alonso, "LTspice: Importing & Exporting PWL Data." Accessed: Apr. 10, 2024. [Online]. Available: <https://www.analog.com/en/resources/technical-articles/ltspice-importing-exporting-pwl-data.html>
- [29] D. Im, I. Nam, and K. Lee, "A CMOS Active Feedback Balun-LNA With High IIP2 for Wideband Digital TV Receivers," *IEEE Trans Microw Theory Tech*, Dec. 2010, doi: 10.1109/TMTT.2010.2086375.
- [30] R. Semiconductor, "BC858B PNP General Purpose Transistor," Jun. 2016.
- [31] O. Semiconductor, "2N3903 NPN General Purpose Transistors," Aug. 2021. [Online]. Available: www.onsemi.com
- [32] O. Semiconductor, "LM317, NCV317 - Voltage Regulator, Adjustable Output, Positive 1.5A," Aug. 2021. [Online]. Available: www.onsemi.com

- [33] F. Semiconductor, "LM78XX (KA78XX, MC78XX) FIXED VOLTAGE REGULATOR (POSITIVE) 3-TERMINAL 1A POSITIVE VOLTAGE REGULATORS," 1999.
- [34] W. Liu and F. Analog, "HiFi Audio Circuit Design Application Report HiFi Audio Circuit Design," 2017. [Online]. Available: www.ti.com
- [35] W. Kester, "Ask the Applications Engineer - 13: Confused about Amplifier Distortion Specs?," 1993.
- [36] J. M. Lourenço, "The NOVAthesis LATEX Template User's Manual. NOVA University Lisbon," 2021. Accessed: Sep. 18, 2023. [Online]. Available: https://github.com/joaom-lourenco/novathesis_word/raw/master/novathesis_word-FINAL-EN.pdf.



