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DESIGN OF ELECTRON TUBE AND SEMICONDUCTOR-BASED AND VOLTAGE STABILISED AMPLIFIER CIRCUITS

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Abstract

In this project, an electron tube circuit consisting of a voltage stabiliser, preamplifier, and final stage amplifier circuit was designed. One of the main aims was to reuse as many components and materials as possible, thereby decreasing the project's ecological footprint. The result is a hybrid electron tube amplifier. The function of the circuits was subsequently measured and analysed using various tests.

Keywords*: electron tube, transformer, voltage stabilizer, amplifier, circuit, PL82, integrated circuit.*

1. Introduction

The use of electron tubes has significantly decreased since the 1980s, although in some areas, their usage is still vitally important. Electron tubes are used in applications where high voltages, high current, or kilowatt scale amplification is required. Although these needs can be satisfied with modern semiconductor technologies, the upkeep cost of those solutions are still high, while their heat output requires complex and expensive cooling solutions **[1]**. Vacuum tubes can be found in households as well, in tube amplifiers. These devices are experiencing a re-emergence in popularity due to their unique sound. Microwave ovens also use high power electron tubes to generate microwaves. While electron tubes have disadvantages, some of them can be mitigated by using semiconductors, creating a hybrid circuit that combines the advantages of electron tubes, and semiconductor technology.

2. Hybrid amplifier circuit

The design of the hybrid amplifier, mostly incorporated reused parts. The frame, electron tubes, parts of the final amplifier stage, and many other parts were previously discarded, but were still functional. This has a great significance in reducing pollution, and also helps keep costs down. Doing this also serves as a secondary goal of this project. Using components from devices that were previously considered non-functional, we acquired data on whether components from these broken devices were worth harvesting or not.

2.1. Pre-amplifier

The pre-amplifier (**Figure 1**) uses E83F SE (single ended) pentodes in A class mode. The E83F **[2]** is capable of a performance up to 1W RMS with 10% distortion.

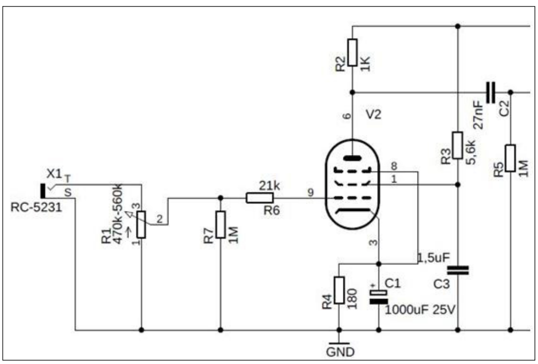

Figure 1. *Preamplification stage (detail).*

This isn't required for general pre-amplification but shows the flexibility of the tube. Maximal anode performance is 2,1W [3]. Triodes were used as pre-amplifiers, as pentodes tend to add a higher level of noise to the signal [4].

The signal arrives at the first junction through a 470–560 kΩ logarithmic potentiometer. Two resistors (R6, R7) are located here.

Resistor R7 is a so-called grid leak resistor. Its main purpose, as its name suggests, is to "leak" the signal to ground. This resistor is responsible for setting the sensitivity of the amplifier. Its value can range anywhere from a few kΩ to 1 MΩ. The larger its value, the more of the signal can reach the electron tube's control grid.

Resistor R6 is the grid stopper resistor. For the signal, the vacuum tube appears essentially as a capacitor. As the electrode capacitance of a vacuum tube is about 300pF [2], this resistor-capacitor connection essentially forms a low pass filter. This is required because high frequencies might enter the electron tube, which can cause a gradually amplified oscillation. To avoid this, the low-pass filter cuts off frequencies above 20kHz.

The R4 (180 Ω) resistor is responsible for setting the operating point of the vacuum tube. This resistor defines the no-load operation. As it works in A-class mode, the tube never fully closes. This resistor limits this current to avoid high anode currents, and unwanted heating. Capacitor C1 serves as negative feedback, which lets the AC signal pass through. This is used to increase the gain of the vacuum tube. Its value may range from 33µF up to 1000µF.

The anode is supplied through the R2 resistor and serves the same voltage-reducing function as the shielding resistor R3. C3 serves as biasing for the shielding. This capacitance must be lower than the reactance of the R3/10 (5,6k/10) value at the lowest frequency (in our case 20Hz). C3 can be calculated using formula (1)

$$C = \frac{1}{2\pi f X_C} \tag{1}$$

where C is the capacitor's value, f is the desired lowest frequency, X_C is the reactance to be approached by the capacitor. Based on this calculation, the capacitor's value should be 1,5µF for optimal operation.

The amplified signal comes from an electron tube's anode. Here, a DC blocking capacitor is needed.

3. Design aspects

To be able to validate the vacuum tube circuits, the circuit had to be designed to satisfy measurement conditions. Sub circuits use optimized base circuits to ensure optimal functioning.

4. Design of voltage stabilised amplifier

A broken measuring device box was used as the amplifier case. As the measuring device also used vacuum tubes, the transformers found inside were perfect for this project as well. The box was also large enough to house the tubes and the circuit itself.

The amplifier (Figure 2) uses semiconductor diodes, which were chosen due to their small size and higher efficiency. Four BY238 diodes were used for rectifying high voltage, while one was placed in the voltage stabilizer circuit to prevent backwards voltage. The KBL06 rectifying bridge provides direct current to the final stage. 1N4003 diodes provide DC power to the heating elements. The device comprises three parts: power supply, pre-amplifier stage, final amplifier stage. The power supply (Figure 3) uses a transform-

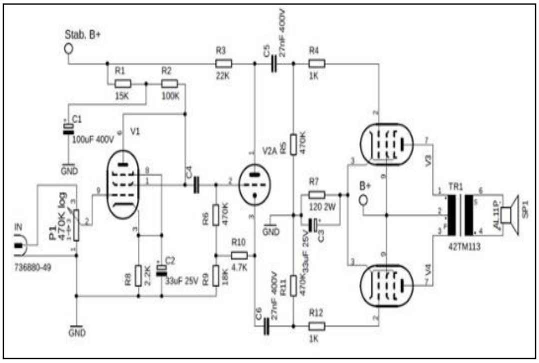

Figure 2. *Amplifier circuit (detail).*

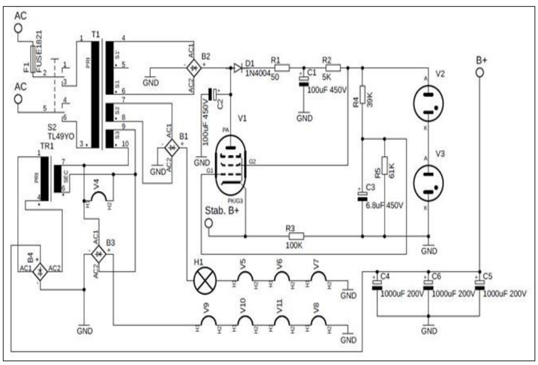

Figure 3. Power supply.

er which has multiple outputs and is capable of operating at 110–127, and 220V. The power supply contains a voltage stabilizer, which provides the pre-amplifier's sensitive circuit with a stable 188V, independent of load, or input voltage. This voltage level was found to be the best for the pre-amplifier and phase-reversing tubes, as they only operate from 150V to 200V [5, 6]] without deterioration. Other than the stable power supply, the end stage only contains a simple circuit. The transformer's 10V output is connected to another transformer's secondary coil, so the final result on the primary coil of the second transformer is 180VAC. After rectifying, the DC voltage is 120V under load which is suitable for the PL82 electron tubes (the voltage recommended by the manufacturer is 170V [7].) This circuit does not require a stable input.

4.1. Voltage stabilizer

The voltage stabilizer circuit provides a stable voltage, independent of the momentary load, or fluctuations in the mains power. This circuit uses 3 vacuum tubes: one radial beam pentode and two voltage reference tubes. The 85AT2 reference tubes provide 85V each as reference [8], which is 170V connected serially. The 170V voltage will be present as long as voltage doesn't drop below the opening voltage of the reference tubes. If due to load or mains power fluctuations the voltage differs from the reference, the pentodes open more, to keep the voltage stable on their output [9]. The circuit provides a voltage of 188V in this project.

4.2. Amplifier

The amplifier has three main parts: pre-amplifier, phase-reversing circuit, and a push-pull final stage. The signal first reaches the pre-amplifier, where an EF86 pentode is used in triode mode. If we use it in this mode however, the noise level significantly decreases, making it suitable for low signal levels [5]. The signal then enters the phase-reversal stage. As the electron tubes cannot operate in reverse polarity mode, a phase-reversing circuit is required for the operation of the push-pull configuration tubes' negative amplitude mode. This function is provided by a PCC88 vacuum tube, which is a double triode [6]. The anode of the triode controls the push-pull circuit's positive control grid, while the triode's cathode controls the negative control grid. With this solution, the final stage can create a negative amplitude signal. As the electron tubes operate at a high voltage and low current, the speaker, which requires high current at a low voltage, cannot be directly driven. To solve this, an audio transformer must be used.

5. Circuit design

The circuit was designed in Autodesk EAGLE [10]. The power supply (Figure 4) and the amplifier circuit's schematics were made on separate pages to improve readability.

The heating elements are connected in series. This is for both design and safety reasons. As the transformer was designed for serially connected heaters, the desired voltage is achieved by splitting the existing high voltage.

The radial beam pentode, as it requires 25V [11] heating voltage, can be directly connected to the transformer's secondary coil. The four PL82 pentodes are connected as follows: two are connected in series, and two groups of these serially connected tubes are connected in parallel. This makes it possible to operate them from the 30V achieved with rectification. The two EF86, and PCC88 tubes found in the pre-amplifier circuit require 6.3 [5] and 7 [6] volt heating, and as such, a

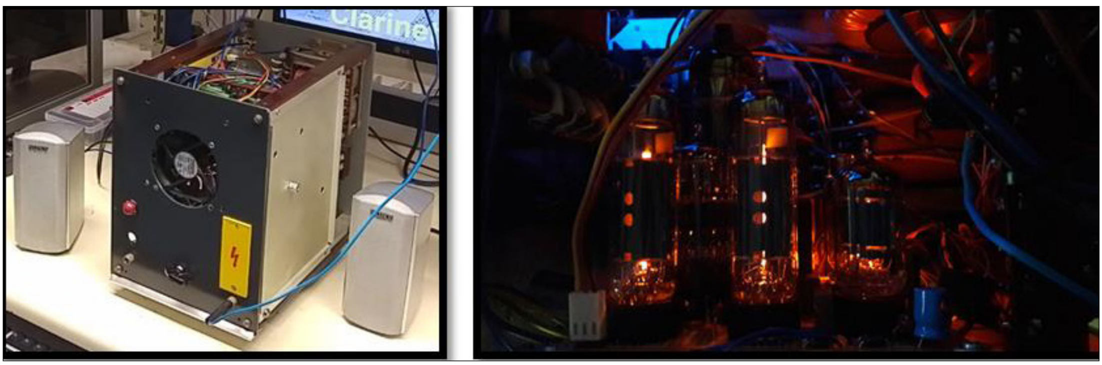

Figure 4. *Manufactured amplifier.*

6.3V light-bulb had to be added to the 30V circuit to set the voltage levels.

Electron tube circuits do not require complex circuits, as they operate linearly.

6. Results

6.1. Operation of the amplifier

The complete amplifier circuit is capable of 3W of performance, per channel, with a 4Ω load. The frequency response of the amplifier circuits was measured with a Rhode&Schwarz RTB2004 digital oscilloscope. Measurement range was 20Hz to 20 kHz with a 2Vp-p (peak to peak) voltage. The built-in function generator was used to generate these frequencies.

To prepare the measurements, a 1 kHz frequency 2 Vp-p sine signal was connected to the pre-amplifier's input. Then, the end stage volume was increased until it reached 1W of output power. When these parameters were achieved, the test could begin. The test starts at 20Hz, and logarithmically increases up to 20kHz. In an ideal case, the Bode-plot is completely linear, however, there are numerous components in the system which affect the shape of the diagram. These are mostly capacitors.

On the diagram (**Figure 5**) gain can be seen with an orange color, and with blue, the phase. We can observe that frequency response is relatively straight. There's a break around 40Hz, which is completely acceptable. There's also a break starting at 10kHz, which can be explained by the limitations of the integrated circuit, which is unable to provide the required performance without distortion. To this end, a supplementary circuit had to be built in to limit the upper segment of the frequency range, which is a necessary step with this IC family.

The right channel's diagram shows negligible difference compared to the left. There's a small downwards curve between 1kHz and 6kHz. This can be explained by the manufacturing tolerances of capacitors and resistors. This difference however is inaudible, and as the two channels behave essentially the same, we can say that the stereo effect is created for the listener.

6.2. Electron tube amplifier

The gain of the vacuum tubes can be calculated using the following (2) equation:

$$Gain = \frac{\mu * R(L)}{R(L) + r(p)} \quad (2)$$

where μ is the electron tube's gain, *R(L)* is the load in ohms, and *r(p)* is the anode resistance in ohms **[12]**.

The amplifier circuit's frequency response was tested using a function generator (Metex MXG-9802A), a digital oscilloscope, (Hantek MSO5102D) and a multimeter (AXIO AX-588B). The measurement range was set from 20Hz to 20kHz, and the results were visualized using VituxCAD **[13]** per channel. The frequency response of the left channel can be seen on **Figure 6.**

As the amplifier's transformer is not a specialized audio transformer, minor non-linearities can

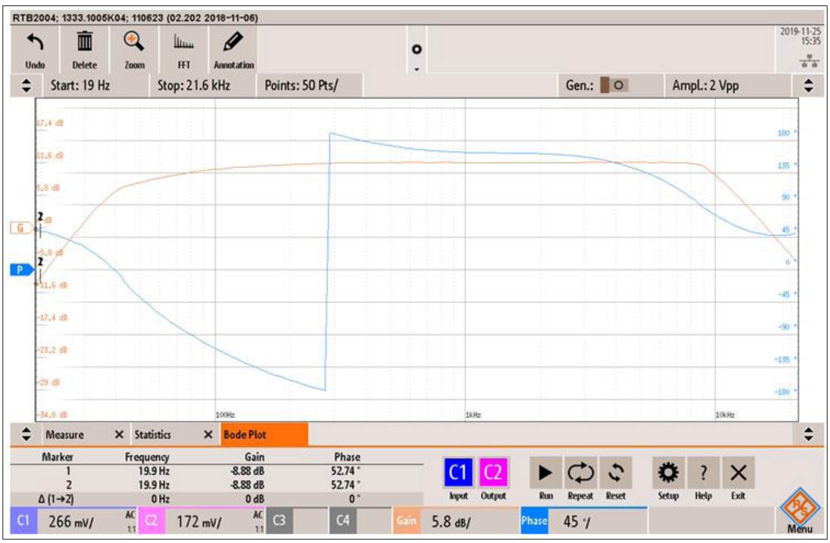

Figure 5. *The left channel's Bode-plot.*

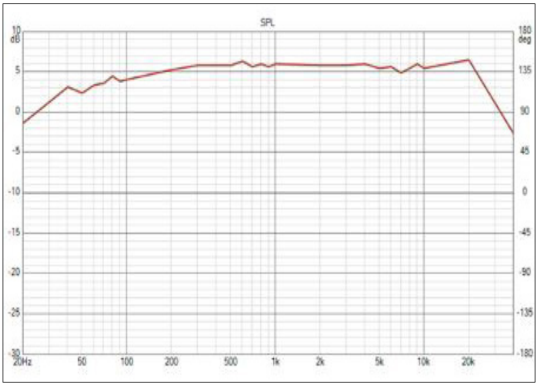

Figure 6. *The left channel's frequency response.*

be observed, however, to the human ear, these imperfections are barely noticeable. This is especially so, if the connected speaker is lacking in frequency response the first place.

The right channel results are similar to those for the left. The stereo effect is noticeable to the listener, as both channels have the same frequency response and volume.

7. Summary

The electron tube, hybrid voltage regulator and amplifier circuit were built. In this circuit, various measurements were performed concerning its stable operation. Moreover, these circuits have shown modern uses for the reclaimed devices, working together with modern semiconductors. The project shows future promise. The transformer heating circuit can be replaced with a switch mode one. Using audio transformers, better frequency response could be achieved.

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