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Design of amplifiers in LTspice

Aspects on the usage of spice-ware in the work of designing an electron tube amplifier

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Abstract

Design av förstärkare i LTspice

Design of amplifiers in LTspice

Per Normann

Among users of guitar amplifiers there is a tendency of being enthusiastic about the usage of electron tubes in amplifiers. Further to shy away from the usage of transistors as gain devices. This to the extent that new technology is generally avoided. In this paper however a software tool called LTspice is used as an aid in the design process of an guitar amplifier. Electron tube spice models are examined and used in the process. The amplifier being designed in this paper has two types of electron tubes, 4 EL84 in the power section and 2 ECC83 in the pre-amplifier. The output of the amplifier is 30 to 35 W.

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Sammanfattning

Bland användare av gitarrförstärkare finns en tendens att vara entusiastisk över elektronrör. Ofta till den grad att ny teknik undviks generellt i sambamd med gitarrförstärkare. I den här uppsatsen undersöks möjligheterna att använda spice-mjukvara som hjälp i designarbetet. I användandet av spice-mjukvaran används så kallade spice-modeller för att emulera verkliga elektronrör. Hur bra dessa spicemodeller återger vissa egenskaper av elektronrör undersöks också.

En läsare bör ha grundläggande kunskap inom elektronik,, dataanvändande, viss erfarenhet av spice-mjukvara underlättar också läsandet. Allt användande av spice-mjukvara sker i programmet LTspice som är ett så kallat freeware, dvs. det finns att tillgå fritt på internet. Utöver LTspice används annan mjukvara, tex spice modeller. All den mjukvara som används presenteras med en kortattad beskrivning hur den kan införskaffas via internet.

Förstärkaren som designas här har 4 st EL84 I slutsteget och 3 st ECC83 I försteget. Förstäkrarens så kallade maxeffekt, maximal förstärkning innan distortion förekommer, är mellan 30 och 35 W.

1 Introduction

1.1 History of amplification

In 1800 Alesandro Volta presents a galvanic element. With this invention it is possible to create electrical voltage. Three quarters of a centery later Maxwell, J.C put forward [1] which is commonly known as Maxwell's equations. Maxwell's equations theoretically describes electromagnetic waves and thus paves the way for new advances in the field of electricity. In [2] Hertz, H verifies Maxwell's theories in a series of experiments. When the eighteenth century draws to an end the Italian inventor Marconi, G constructs the first signal transmitter [3] by utilizing the theoretical achievements done by Maxwell and Hertz.

When the electron tube [4] is invented by Forest, D in 1907 the transmitted signal can be amplified on the receiving end. 1920 the refinement of the electron tube makes it possible to amplify the signal being sent. At the middle half of the 20th century the electron tube is the main component in gain stages in electronic devices.

A theoretical transistor [5] is presented in 1948 by a group of scientists at the Bell Laboratories. Eight years later, in 1956, the same group presents a working transistor and recives the Nobel price for this. The transistor's advantages over the electron tube leads to a rapid decline in the usage of electron tubes. By the end of the 20:th century the usage of electron tubes is almost non-existent. There is however one field in which electron tubes still are used frequently. In HiFi-amplifiers and guitar amplifiers the electron tube is still popularly used. The electron tube has some features that makes it popular to use in amplification of sound.

1.2 Why electron tubes

From the emerging of the transistor till present days the development of transistors in integrated circuit has been extensive. It is now possible to emulate electron tube like amplifiers by the help of software tools in computers. This is however a subject of strong opinions. Throughout the guitar amplifier community the fact whether an emulated electron tube is on par with or even close to the real thing seems to be a big no no. The interested reader is encouraged to join an on-line forum or just read comments regarding this subject. While this text is written, 2013-05-26, the Google search *transistor vs. tube* renders over 22 million hits.
The idea that the electron tube is irreplaceable has a huge affect on amplifier market. Designers and vendors of amplifiers have to comply with this supply and demand situation. With a market craving for electron tube amplifiers, new inventions is not likely to be profitable in years to come. In the race of cutting costs to raise profit many amplifier producers manufacture transistor amplifiers. These transistor amplifiers are often presented as a low cost alternative to electron tube amplifiers. In addition to this misleading marketing of these devices is often used. Guitar amplifiers with transistor technique are often labelled in such a way that the user is lead to believe that the amplifier is a electron tube amplifier. Valvestate, Tubetrans, Valvetronix are just a few of these somewhat misleading names, note that in British English electron tubes are commonly known as valves.

1.3 Old technology - new tools

Other aspects of guitar amplifiers should however be able to benefit from new technology. No mater if a computer emulated electron tube amplifier is a far cry from the real thing or not software tools can be of aid in the design of a tube amplifier. In this paper the underlying technique of electron tube amplification is investigated to give an insight in how a common electron tube amplifier works. This knowledge is then used to design an electron tube amplifier in the software tool LTspice.

2 Theory

In this section a survey of the components in an electron tube amplifier is presented. The survey is meant to give the reader a fair idea of how each part of how a standars electron tube amplifier works. The text is also meant to display and explain customary construction solution. A reader of this section should have basic knowledge of alternating current electronics.

2.1 Electron tubes

2.1.1 The triode

Okasura, S. *et. al.* surveys the historical usage and development of electron tubes [6]. An in depth examination of the triode is presented. A common way of constructing and vend contemporary triodes is in pairs mounted in vacuum tubes. One of the predominant electron tubes is the ECC83 which is two EBC91 triodes package in one vacuum tube. Due to the wide spread usage in Hi-Fi and guitar amplifiers the ECC83 is one of few types of electron tubes still being produced in large numbers.

To get a triode to amplify a signal the triode is connected to the signal wire, to ground and to wires that supply heater current. The basic structure of the triode stage is presented in Illustration 1.

In a triode the amplification is obtained by inducing and controlling an electric field between the anode and the cathode. The cathode is heated to lower the threshold for the cathode to emit electrons. Electrons are prone to stream from the negative cathode to the positive anode. The electric stream from the cathode to the anode in the triode induces a current. By controlling the electric field the current through the triode is indirectly controlled. The control mechanism is achieved by applying a negative voltage at the gird between the anode and the cathode.

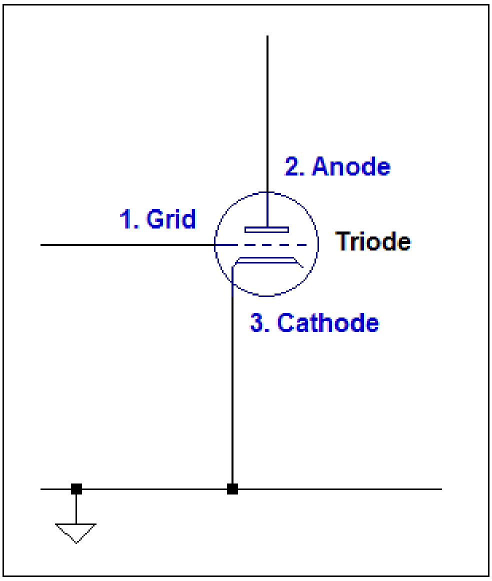

Illustration 1: The in-signal is received at the grid connection 1. The anode connection 2 sends the amplified out signal. The cathode connection 3 is grounded over a resistor.

The way the anode, cathode and grid voltages are balanced is often referred to as bias. Low negative bias voltage at the grid makes it easy for electrons to flow from the anode to the cathode. Conversely, a high negative bias voltage at the grid prevents the electrons flow from the anode to the cathode. This behaviour allows for variations in the grid voltage to appear at the anode. By superimposing an electric signal on the bias voltage at the grid the signal is transferred from the grid to the anode. In gain stages a triode amplifies the signal appearing at the anode. The EBC91 triode's amplification factor is 100.

2.1.2 The beam power pentode

The beam power pentode is similar to the triode in many ways. In a power pentode there are three grids instead of the triode's single grid. In order from the cathode to the anode the first grid is the control grid, it functions like the grid in the triode. The second grid is the screen grid that focus the electron beam so that more of the jumping electrons make it to the anode. The third is suppressor grid that hinders electrons to jump back to the screen grid. This is necessary because the screen grid is often kept at

positive voltages.
In this paper the EL84 is used in the power section of the amplifier. The El84 is a widely spread pentode that is still being manufactured because of the popularity in Hi-Fi and guitar amplifiers.

2.2 The grounded cathode gain stage

The grounded cathode gain stage is a fundamental building block in electron tube amplifiers, it is characterised by the triode and the topology of the stage. In Illustration 2 the schematics of a grounded cathode gain stage is outlined. The main idea of the grounded cathode stage is to amplify a small input signal into a larger output signal. An ideal gain stage amplifies the in-signal with a linear frequency response and no distortion. However, in guitar amplifiers a gain stage is often deliberately designed to distort the amplified signal and alter the frequency response.

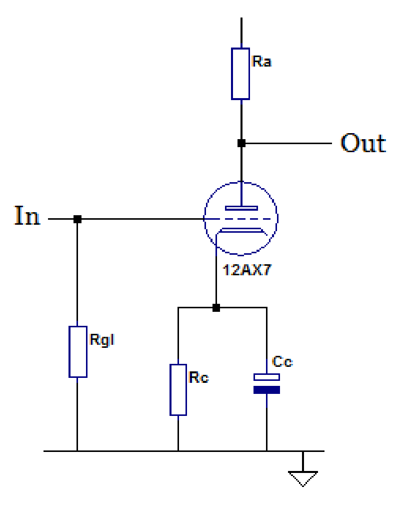

Illustration 2. A grounded cathode gain stage.

2.2.1 Triode characteristics

A data sheet displaying the static anode characteristics is often used when a triode gain stage is designed. There seem to be many different names used for this diagram, in this paper the diagram will be called static anode characteristics diagram.
An anode characteristics diagram holding the data of the ECC83 electron tube is displayed in Appendix A1. The diagram displays the current I_a and voltage drop U_a from the anode to the cathode. The curved lines shows the voltage drop U_{gc} from the grid to the cathode. These lines are often referred to as grid curves. These entities are central while setting up a common cathode gain stage.

2.2.2 The anode load line

In a grounded cathode gain stages there is a resistor R_a connected to the anode of the triode. With a voltage applied on R_a, the triode and R_a are in series. If there is no current flowing through the triode there can be no voltage drop over the R_a, consequentially by Ohm's law, all the voltage drop is over the triode. Assuming that a point A can be defined in the static anode characteristics diagram at $A = (U_a = U_{max}, I_{a1} = 0)$, Appendix A2. U_{max} is commonly known as plate voltage. If all available current flows through the triode all the voltage drop will be over R_a. By applying Ohm's law it is possible to calculate I_a,

$$I_a = \frac{U_a}{R_a} \, . \tag{1}$$

With no current flowing through the triode a point $B = (U_a = 0, I_a = U_a/R_a)$ can be defined in the anode characteristics diagram, Appendix A2. Although these two extreme points are not seen in any functioning triode stage they are useful when a triode stage is design. Since Ohm's law is linear a straight line can be interpolated between these points. By merging these ideas a function (2) can be put together for calculations of the anode load line in a grounded cathode gain stage.

$$I_a(U) = \frac{U_a - U}{R_a} \tag{2}$$

The dashed line in Appendix A2 forms an exemplified load line of a ECC83 triode grounded cathode gain stage. The load line is central in the analysis of a electron tube circuit and hence the triode stage. As seen in (2) the anode load line of a triode stage can be adjusted simply by altering R_a or U_a. The load line and the grid curves intersects, see Appendix A2. These intersections shows what U_a and I_a will be for different U_{gc}.

2.2.3 The cathode load line

Like R_a on the anode side of the triode there is a cathode resistor R_c connected on the cathode side. Similar to the anode load line it is possible to draw a load line for the cathode. If all current is flowing through R_c the voltage drop from the grid to the cathode in the triode can be calculated by Ohm's law (1). Adjusting the cathode load line is usually done after the set up of the anode load line. This is assumed here, hence I_a is assumed to be known. A point $C = (U_{gc} = -I_a R_c, I_a = U_a/R_a)$ can now be marked in the static anode characteristics diagram in Appendix A2. The cathode load line has a linear part, but it is not linear close to 0 V. The grid curves in the anode characteristics diagram have a wobbly behaviour at 0 to 50 V, anode voltage. This suggests that it is not possible to interpolate a straight cathode load line in this interval. Ohm's law is used to calculate a second point D in the static anode characteristics diagram in Appendix A2 with values chosen outside the low anode voltage range, $D = (U_{gc} = -I_a R_c, I_a = 0.5)$. By putting together these ideas a way of describing the cathode load line can be defined,

$$U_{gc} = -\frac{U_a R_c}{R_a} . \tag{3}$$

Graphically the same can be done by interpolating a line between point C and D in the anode characretistics diagram. An interpolation between *C* and *D* forms the cathode load line. The blue dashed dotted line in Appendix A2 exemplifies a cathode load line. The intersection between the anode and the cathode loadlines is the bias point.

2.2.4 Bias point

The bias point is the operation point of the triode. When the operating point is set in an grounded cathode gain stage it is possible to determine amplification and other features of the stage. By shifting the bias point it is possible to induce more or less gain. Note that the bias point of the grounded cathode gain stage is determined by the values of U_a R_a and R_c.

2.2.5 Stationary amplification

Bijl's equation states that,

$$\mu = r_a g_m , \tag{4}$$

where μ is the amplification factor, r_a is the inner anode resistance and g_m is the transconductance of the triode. Bijl's equation is convenient because it states a dependency that make it possible to calculate r_a. If r_a is known the amplification of the grounded cathode gain stage can be calculated. μ is listed in most electron tube specifications. It can also be derived from a statis anode characteristics diagram,

$$\mu = \left. \frac{\partial U_a}{\partial U_{gc}} \right|_{I_a} . \tag{5}$$

The transconductance g_m is an entity that models the triodes ability to convert a voltage change into a current change. *m* is to indicate the maximum achivable gain of the gain stage. If U_a is kept constant g_m is,

$$g_m = \left. \frac{\partial I_a}{\partial U_{gc}} \right|_{U_a} \tag{6}$$

The inner resistance r_a is deriven by keeping U_{gc} constant,

$$r_a = \left.\frac{\partial U_a}{\partial I_a}\right|_{U_{gc}} . \tag{7}$$

It should be mentioned that these three entities vary slightly depending on the triodes bias point. A reading from the static anode characteristics diagram is often a better choise than using values listed in tube specifications. As mentioned these three entities, μ, r_a and g_m are readable in the static anode characteristics diagram. An example, the amplification factor is read by checking what ΔU_a is when $\Delta U_{gc} = 1$.
The amplification of a grounded cathode gain stage can be derived by assuming that the triode is a perfect amplifier with the gain factor μ. If the amplifier leads a signal current down through any impedance present in the gain stage, all these impedances forms a voltage divider. The out signal in a grounded cathode stage is taken across R_a. To properly calculate the amplification A all impedances down to ground has to be considered [7],

$$A = -\mu R_a \sum_{i=0} \frac{1}{R_i} . \tag{8}$$

Since the difference between the grid and the cathode are amplified any impedance placed in series on the cathode side will appear to be amplified, $\mu * R_c$. Three more impedances forms the total impedance; R_a, r_a, and R_c. The amplification of the grounded cathode stage is

$$A = \frac{-\mu R_a}{R_a + r_a + \mu * R_c + R_c} \tag{9}$$

The minus sign is a result of the fact that an increased grid voltage will lower the anode voltage. In practice this means that the grounded cathode gain stage not only amplifies the in-signal, the in-signal is also inverted. It is possible to calculate the stationary amplification A by using (4) and (9).

2.2.6 Grid leak resistor

When a triode is operating the grid is indirectly heated by the heated cathode. The heat leads to emission of electrons from the grid. This loss of electrons makes the grid slightly more positive charged. Reduced negative grid voltage lowers the threshold for electrons to jump from anode to cathode. This results in more current flowing from the anode to the cathode, hence worsen the heat problem even more. To maintain the grid voltage at a controlled level electrons must be replenished in the grid. A grid leak resistor R_{gl} connected between ground and grid will provide a leakage path for electrons from the cathode into the grid. With a grid leak resistor in place the bias point will be maintained despite heat induced electron emission from the grid.

R_{gl} has to be large enough to hinder the signal to be dumped down to ground. Most electron tube have a maximum listed size of R_{gl}. According to Jones, N. to large R_{gl} will induce noise into the triode circuit and is not desirable [7]. In guitar tube amplifiers the predominant value is $R_{gl} = 1\text{M}\Omega$.

2.2.7 Bypassed cathode

A superimposed signal on the grid makes the grid voltage U_{gc} variable. If a positive going signal enters the grid the current through the triode will increase. This current increases the current through the cathode resistor R_c, which in turn increases the voltage drop over R_c. An increase of current through the triode makes the cathode voltage higher. This combination of increased voltage at the cathode and lowered voltage at the plate decreases the electrostatic attraction across the triode. The result is a reduction of gain.

A superimposed signal of negative direction on the other hand decreases the conduction through the triode. The current through the cathode resistor R_c decreases, hence the voltage drop over R_c will also decrease, according to Ohm's law. This causes the cathode to become slightly more negative which in turn increases the conductivity through the triode, which also reduces the gain.

Not only does these phenomenons reduce the feedback of the grounded cathode gain stage, it also reduces distortion and increases the output impedance. None of these three features are sought for in an guitar amplifier and luckily there is an easy way of cancelling them out. A capacitor C_c at the cathode in parallel with the cathode resistor R_c will inhibit these phenomenons. C_c has the affect that it holds the grid voltage at constant level.

2.3 Coupling capacitor

In electron tube amplifiers many parts of the amplifier are powered by high voltages. Other parts operates at low voltages. This means that a way of shielding DC voltages is needed. Capacitors filters DC voltages and passes AC voltages by preventing current flow through them. AC voltages are transmitted by the oscillating electromagnetic field induced over the capacitor. By adding a capacitor between two voltage potentials no DC voltage will drift by an induced current. Added to the shielding of DC voltages the capacitor's impedance is frequency dependent. Different frequencies of the signal will be attenuated differently. In tube amplifiers each stage is normally separated this way, by adding capacitors between stages. Capacitors used in this way are normally referred to as coupling capacitors.

2.4 Phase inverter

A phase inverter splits the signal into two signals. One of these signals is then phase shifted. The result is two indentical signals that are out of phase. The phase inverter chosen for this project is the long tailed phase inverter. It is a common phase inverter in electron tube guitar amplifiers. The topology of the tong tailed phase inverter is basically two grounded cathode gain stages mirrored against each other.

2.5 Power stage

In amplifiers with multiple gain stages the stage that delivers the highest amplitude attenuation is often referred to as the power stage. This stage is also used to deliver the amplified signal to the speakers. There are different kinds of power stages. In guitar amplifiers a high amplification rate is often desired and for this purpose a push-pull power stages is suitable.

In this paper the electron tube in the power stage is set up very similar to the triode's grounded cathode gain stage. The power stage differes in the way that the grids are used. Instead of one grid three grids are avaliable in a pentode. The grid closest the cathode is used as control grid. The voltage range of the grid is generally on the negative side, with peaks up in the positive voltage range.

Next grid is the screen grid, it is focusing the electron beam from the cathode in a way that more electrons jumps to the anode. The voltage at the screen grid is slightly lower than the anode voltage. This is to hinder electron from jumping back to the focusing grid from the anode.

The grid closest to the anode is connected to the control grid. The negative to low positive voltage range is preventing electrons from being emitted from the anode.

2.5.1 Push-pull class AB

In a class A amplifier a gain device amplifies a signal over the entire period. By adding a mirrored gain device the amplification of the signal can be devided between the two gain devices. One device amplifies to upper part and the other amplifies the lower part of a signal. This is known as a push pull set up. In a push pull configuration it is possible to push amplification devices more. Due to the partition of the amplification work, each gain device only have to be active during the designated part of the signal. By pushing each gain device so that they amplifie a little more than half of the signal amplitude the amplification is in class AB mode. Note that class AB is a combination of class A and B. Class B is when an amplification device amplifies strickly the upper or lower half of a signal. The splitting of the signals is done in the phase inverter, see the section *Phase inverter* for further details. The metaphoric term pull describes the situation when the electrical potential of the two signals are furdest apart. Similarly push describes the situation when they are close to each other. In a class AB set up with two signals out of phase the potential effect increases by raising the maximum voltage swing going to the output transformer.

2.5.2 Output transformer

In electron tube amplifiers the signal is of high voltage and low current in a high impedance enviroment. This is due to the functionallity of the electron tube, see the section *The triode* for details. Loud speakers are low inpedance devices not suitable for high voltage low current signals. A workaround to this mismatch is the output transformer. An output transformer steps down the voltage to more reasonable levels. Normal values in electron tube circuits are in the realms of 300 to 500 voltages. Voltages as high as this is not suitable for speakers with low internal impedance, normal values are 4 to 16 Ω. Connecting an out signal from a electron tube straight into a speaker leads to very high currents trough the speaker. According to Ohm's law,

$$I=\frac{U}{R}=example=\frac{400\text{V}}{8\,\Omega}=50\,A\ . \tag{10}$$

In a push pull power section the output transformer has got two signal connections. Each signal connection should have equal impedances to the a voltage connection. A high voltage connection is used to raise the voltage potential of the circuit. The fact that the two signals are out of phase gives an extra potential difference in the output transformer. Hence the magnitude of the transformer's magnetic field is proportionally to the electric potential in the pulsating voltage in the inducing coil.

2.6 Tone control

2.6.1 Frequency span of guitars

Guitar tuning has altered throughout history. The last hundreds of years the most popular tuning is, E, A, D, G, B, e. This tuning is simply known as standard tuning. The low end of the frequency span in standard tuning is the E string with a frequency of 82 Hz. The highest number of frets on standard guitars is 25. The tone of the high e string at the 25:th fret is approximately 1.4 kHz. Apart from standard tuning there are many different ways of tuning guitars. However, most alternative tunings render approximately the same frequency span as standard tuning. There are guitars with an extra low b-string. This string is about 60 Hz, when played open. It should be mentioned that there are overtones created by guitars. This is due to the fact that some vibrations in the strings have nodes that are pivoted along the length of the string. With overtones taken into account the span in focus should go up at least a couple of kHz over the highest tone on the fret board of the a guitar. The highest frequency audiable by a human ear is however approximately 22kHz. This would imply that a guitar amplifier with a band pass interval of (50, 22k) Hz would amplify all possible frequencies that might be desirable.
The aim of this paper is to present a circuit suitable for a electric guitars.

The characteristics of the amplifier will be fitted to this, solely. But as it happens, most of the commonly used instruments in the world has virtually the same frequency span as guitars. This would imply that in spite of the intention of constructing a guitar amplifier with suitable distortion and frequency response. The amplifier will be suitable for amplifying other instruments to, although, in a guitarish way.
Among different kinds of guitars there are a wide tonal range, often referred to as voicing of the amplifier, or which tonal range different guitars emphasizes. If the user of an amplifier is able to change the tonal response of the amplifier it is possible to emphasize or suppress tonal ranges. One way of controlling the voicing of the amplifier is to incorporate filters for different frequency ranges. These filters are often adjusted so they overlap each other in a way that they together cover the normal frequencies of guitars.

2.6.2 Tone stacks

The Fender, Marshall and VOX tone stacks, commonly known as the FMV tone stacks are often referred to as the most widely spread tone stack. No statistics have been found proving this assertion, but many tone stack are are unarguably spin-offs or plain copies of these. The FMV tone stacks in turn are spin-offs or derivatives of the Williamson, D. T. N. tone stack [8].
The Fender AB763 tone stack in the Illustration 3 consists of two main things. Three capacitors working as coupling capacitors and passive filters formed by the potentiometers and the capacitors. Technically speaking these three filters are passive filters, made up by resistors and capacitors. The basic building blocks are the highpass and the lowpass filters. Highpass filters attenuates low frequency signals and vice versa a lowpass attenuates high frequency signals.
The limit where a filter suppresses 3 dB of the signal is called cut-off, or cut-off freqeuncy. By combining these two filter types a band-pass filter can be constructed. The frequency span between the low- and high-cut frequencies is called band width.
Both lowpass and highpass cut-off frequencies are calculated in the same

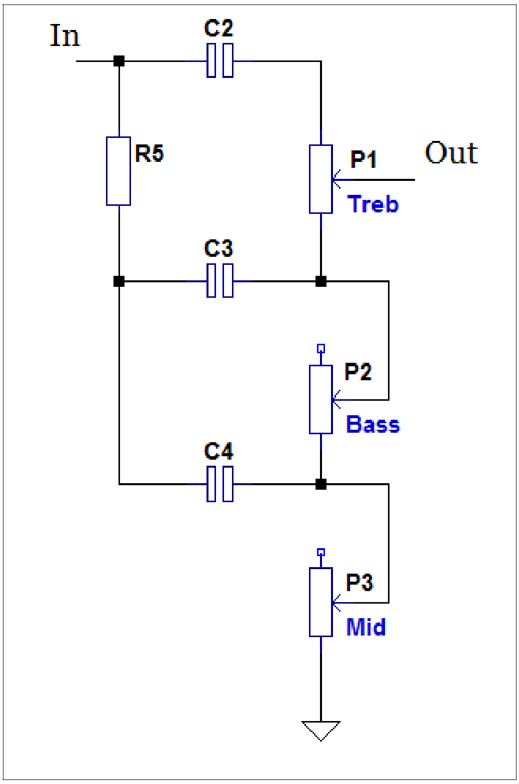

Illustration 3. The AB763 Fender tone stack. A refined version of the Williamson, D.T.N. tone stack.

way even though the topology differs, according to Physics Handbook,

$$f=\frac{1}{2\pi R C} \tag{11}$$

2.6.3 Treble

The capacitor C2 and the potentiometer P1 in Illustration 3 isolated forms a high-pass filter. Signals with frequencies lower than the cut-off frequency are suppressed by C2. P1 forms a variable resistor between C2 an Out. By altering the setting of P1 the frequencies going through C2 are attenuated. If C2 is chosen in such a way that the cut-off frequency is in the higher part of the amplifiers range, P1 gives the user a way to adjust level of the high frequency range of the amplifier.

A side effect of the fact that P1 varies the resistance in the high-pass filter is that the cut-off frequency is slightly altered. Although this effect is reduced significantly by P2 and P3. These two potentiometers form a resistance to ground in the Treble low-pass filter.

If the hole tone stack circuit is considered, P1 forms a blender for high frequencies and middle, bass frequencies. In fact raising the level of the P1 potentiometer will reduce the Middle and Bass levels slightly.

2.6.4 Bass

Once again the circuitry in Illustration 3 is analysed by isolation some components. The resistor R5 and the capacitor C4 forms a low-pass filter at the node between them. At this node the potentiometer P2 and the capacitor C3 forms a high-pass filter. It is this low-pass filter that makes it possible for the user to control the frequencies in the bass span. The high-pass filter C3 and P2 is not used to alter the frequency response of the tone stack. The main purpose of C3 is to shield DC voltages from leaking through the tone stack.

2.6.5 Middle

The potentiometer P3 in Illustration 3 is a shunt to ground. This implies that the Middle control needs bass and treble frequencies to be able to alter the middle frequency response of the tone stack. An analogy could be to imagine bass and treble as two hills. The Middle potentiometer can only fill the wally, not build a hill of its own.

3 Simulation and design

3.1 Electron tubes in LTspice

In this paper three different libraries of electron tube spice models is tested. All can be found on internet, the Rydel, Duncan and Koren electron

tube spice models. For the interested reader, search for *spice electron tube models* in some search engine to find them. The TLspice user adds a reference to the search path to the downloaded library so that LTspice can access the library. Then the propper component symbol is added by the user of the circuit editor. With these two steps the models are ready to be used. A wide range of different analysis can be made when a simulation is done.
To assess the quality of the electron tube models used in this paper the anode characteristic is examined. By incrementing the anode and grid voltage in the same intervals as those presented in a static anode characteristics diagram the anode characteristics of the spice models is determined.
The three models clipping behavior is examinde by setting up a test where they are pushed into clipping. The electron tube models are also tested by setting them up in a test where a wav file is created from the out signal. This output file is used as a audio reference to a real electron tube. In the audio tests the main focus is to establish whether the electron tube models are able to mimic the clipping in a real electron tube. None of these audio tests can be presented in this paper, obvious reasons.

3.1.1 Tests of the ECC83 tube models

The electron tube chosen for the grounded cathode gain stages is the ECC83. A wide range of ECC83 models are initially tested, each electron tube model library contains several spice models of each electron tube type. The tested models are assessed and three candidates are chosen for further studies. The anode characteristics of the three tested models are presented in Appendix A4. The data of the real ECC83's static anode characteristics diagram from ValveWizard's LoadLinePlotter. The clipping behaviour of the ECC83 is tested and presented in Appendix A5.
In this paper the Rydel, C. ECC83 model is chosen for the design work in LTspice. The reason for this is that the Rydel model's anode characteristic is considered closest to the real ECC83. This assessment is done by graphically examine the plot in Appendix A4. Further, the clipping behaviour is considered to be the closest one to a real ECC83 electron tube. If these three electron tube models are to be ranked the next best after Rydel's model would be the Duncan model. Judging by Appendix A4 and A5 the worst of the three is the Koren model. Both Rydel's and Duncan's electron tube model are fairly close approximities in the anode characteristics. Rydel's spice model is a closer approximation than Duncan's in terms of clipping behaviour.
Although the ECC83 models clearly differ in the obtaind data it is not possible to distinguish them from each other by listening to audio simulations. This discovery lowers the expectations that a good simulation can be made of a electron tube amplifier. Good in the sense that the simulated amplifier will reproduce all the properties in a credible way. In spite of this lack of divergence and weakness in clipping situations the work of designing a tube amplifier in LTspice is far from wasted. The

performance in linear situations still provides a vast insight in the circuitry and the feature of it.

3.1.2 Tests of the EL84 tube models

EL84 electron tubes are used for the power section of the simulated amplifier. EL84 is a pentode with a different kind of anode characteristics than the ECC83 electron tube. As for the ECC83 electron tube the anode characteristic is plotted by the aid of LTspice analysis tools. For this assessment no digital version of the measured anode characteristics from a real EL84 is used, the reason being that no digitized version is found. None of the electron tube models found differed in the anode characteristics assessment. In Appendix A3 the anode caracteristic for the Ryden EL84 model is presented. The EL84 model used differs from the characteristics of a real EL84 in the sense that the anode characteristics of a real EL84 is a bit indistinct, or wobbly in the low anode voltage range, 0 to 100 V. None of the models tested in this paper emulates this behaviour.

3.2 The grounded cathode gain stage

A grounded cathode gain stage is set up in LTspice according to the section *The grounded cathode gain stage*. With initial values of R_a, R_c, R_{gl} and C_c the circuit is tested. After testing and tinkering in LTspice a stabile version is set up. The frequency response of the gain stage is monitored to determine whether a linear frequency response is achieved. The final values of the grounded cathode gain stage is presented in Table 1.

Table 1. The components in the grounded cathode gain stage

U_a	330 V
R_{gl}	1 MΩ
R_a	220 kΩ
R_c	1.5 kΩ
C_c	4.7 µF

All values are chosen so that they are from the standard range of electric components. The anode voltage is set to 330 V due to the fact that a long term goal of this work is to actually build the amplifier simulated in this paper. It happens to be that I have a transformer that gives approximately 330 V after rectification. The frequency response of the modeled grounded cathode gain stage is presented in Appendix B1. Note the plateau between ~100 to ~50 kHz. The frequenies of interest, see section *Frequency span of guitars*, are satisfactory amplified. In Appendix A6 the loadlines of the LTspice simulation of the grounded cathode stage is presented. The circuit of the modeled grounded cathode gain stage is outline in Appendix C1.

3.3 Pre amplifier

The pre-amplifier is constructed by adding a tone stack inbetween two grounded cathode gain stages, see Appendix C2 for details. In the set up of the tone stack the freeware Tone Stack Calculator is used to set up initial values of the tone stack. These initial values are chosen in a way that a, somewhat, linear frequency response of the tone stack is obtained. With the tone stack settings from the Tone Stack Calculator the pre amplifier's frequency response is monitored. In Appendix B2 the frequency response of the pre amplifier is presented.
Note that the frequency response of the pre amplifier is not linear, rather it has got two distinct humps. This is not alarming as the power section can be balanced in a way that evens out this.

3.4 Power section

A power section is constructed by merging the inverter, the set up of the power electron tubes and the transformer. This time LTspice was used in a more active way than in the designing of the pre amplifier. Instead of predetermine the values based on charts etc. all work is done LTspice. All parts are monitored during the design process by the aid of tools avaliable in LTspice. The circuit of power section of the amplifier in this paper is presented in Appendix C3.

3.4.1 Phase inverter

The phase inverter in the designed electron tube amplifier is a revised version of the long tail phase inverter commonly used in Fender amplifier. The Fender long tail phase inverter is in turn a version of the Schmitt phase inverter. The main difference between the designed phase inverter and the Fender long tailed phase inverter is the triode used to drive it. Fender uses a ECC81 triode to drive the phase inverter, here a ECC83 is used. The components C9 also differs, see Appendix C3 for details. The C9 capacitor is a shunt capacitor used to suppress high frequencies [9]. Judging by the plot in Appendix B1 the cut-off frequency in the pre-amplifier very high, much higher than what is audible by a human ear. Suppressing frequencies out of the audible range is a way of prevent undetectable high frequencies oscillation.

3.4.2 Output section

The output transformer of this amplifier is set up by merging three coil components, *L1*, *L2* and *L4* in the LTspice circuit, see Appendix C3 for details. The impedances of these components are arbitarly set to, *L1* = *L2* = 4 kΩ and *L4* = 8 Ω modeled after a AC30[1] amplifier. Normally an output transformer has more than one output impedance connection, not just one as in this example. The impedance of a normal speaker is 4, 8 or 16 Ω which has to be matched against the out impedance of the output

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[1] AC30 is a Vox electron tube amplifier with 4 EL84 in the power section.

transformer.
The primary adjustment of the output section is done by using a wav file as input signal and assess the result, or sound of the amplifier. When the output wav-file is judeged to be well balanced, in other words the subjective assessed to sound good, an anode characteristic analysis is done. In Appendix A7 the anode characteristics for the power tube set up is displayed.

3.4.3 Power tubes

The set up of the power tube is very similar to a grounded cathode gain stage. The pentodes, EL84, are biased negatively by superimposing a negative voltage at the control grid. In Appendix C3 V2 provides negative bias voltage.

3.5 Amplifier

In the merging of the different parts of the amplifier extensive testing is made. Several frequency sweeps are made with different tone stack settings. The frequecy response of these sweeps are presented in Appendix B3. The volume control is constant through this analysis. The simulations shows that the tone stack is able to alter the frequency respons. To adjust the tone stack to the final version of the amplifier a calibration is made.

3.6 Calibrating the tone stack

In an attempt to make each tone control affect the amplification of the corresponding frequency range equally much the range of the controls were matched. The way of achieving this is to plot the amplification in the bass, middle and treble range for the corresponding control. The matched plot is presented in Appendix D1. The logarithmic progression of the curves are due to the logarithmic potentiometers used in the tone controls in the LTspice simulation.

4 Results

An electron tube amplifier was designed in the software LTspice. The amplifier has 4 EL84 electron tubes in power section and 2 ECC83 electron tubes in the pre amplifier. The simulated amplifier is balanced to give a minor break up and a linear frequency response. The maximum output is 30 to 35 W.

5 Design software

5.1 Tone Stack Calculator 1.3

Tone Stack calculator is a software that simulates some of the most common tone stacks found in electron tube guitar amplifiers. The topology of each tone stack is presented along with the possibility to alter the values of components in each circuit. The user can alter the control potentiometers and see the result instantaneously. Compared to developing and testing tone stacks in LTspice the Tone Stack Calculators approach is much faster. It is however not possible to alter the topology in Tone Stack Calculator. The user is confined to the tone stacks available in the software.
Tone Stack Calculator is developed by Duncan Amplification. It is a freeware and can be found and downloaded on the internet: http://www.duncanamps.com/tsc/download.html. The only drawback is that it is confined to Windows.

5.2 LoadLinePlotter

The LoadLinePlotter is a spreadsheet holding data of electron tubes. This data is presented in static anode characteristics diagrams. The user can insert values of anode, cathode resistors and anode voltage. By doing this the anode and cathode loadlines are presented in the static anode characteristics diagram. The LoadLineplotter is constructed by the ValveWizard, and can be downloaded at, http://www.valvewizard.co.uk.

5.3 LTspice IV

In this paper most simulations of circuitry are done in the software LTspice. LTspice offers many different analysis tools to be used on simulated circuitry. The user inserts a circuit with electronic components and sets up the premisses for the simulation. When an simulation is done data can be obtained by using LTspice extract tool. In this paper all data from the simulations is inserted direct into a chart editor in the word processor used to write this paper. Pictures of circuitry is extracted by using LTspice's bitmap format extractor. The extracted bitmaps are slightly edited in a image editor before thay are pasted into this document. Circuitry is inserted by the usage of the LTspice circuit editor, components are dragged and dropped in place. One of the avaliable analysis tools is frequency sweeps. By setting up start and end frequency etc. the user can one click to get a Bode plot of a circuit (one click, in the sense that the user left clicks on a point in the of interest and gets a Bode plot). This tool is used on several parts of the circuit in this paper. The phase plot is however left out in most of the plots since shifts in phase is not audible. Audio tests are made by using an other feature of LTspice. LTspice can take wav files as input and create wav output files. This feature gives the user the ability to create simulations of how the circuit, for instance an amplifier, might

sound. A third feature of LTspice is that it is possible to monitor voltages and currents in circuitry. This feature is used to render anode characteristics diagrams of the electron tube models.
LTspice is a free-ware and can be downloaded from Linear Technologies. There are no opted versions for usage on Linux or mac. Linux and Mac users have to run LTspice in wine. The curious reader is encouraged to test the freeware. It can be found and downloaded from:
http://www.linear.com/designtools/software/

6 Acknowledgement

I like to thank Kjell Staffas for embarking on an expedition back in time with me. A time when there were no the transistors.
A big hug to my parents for all the fun and games with my kids when I wrote this paper.
A big thanks to my family for letting me see what really matters in life.

7 Literature list

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[2] Hertz, H. (1887) Electric waves: being researches on the propagation of electric action with finite velocity through space
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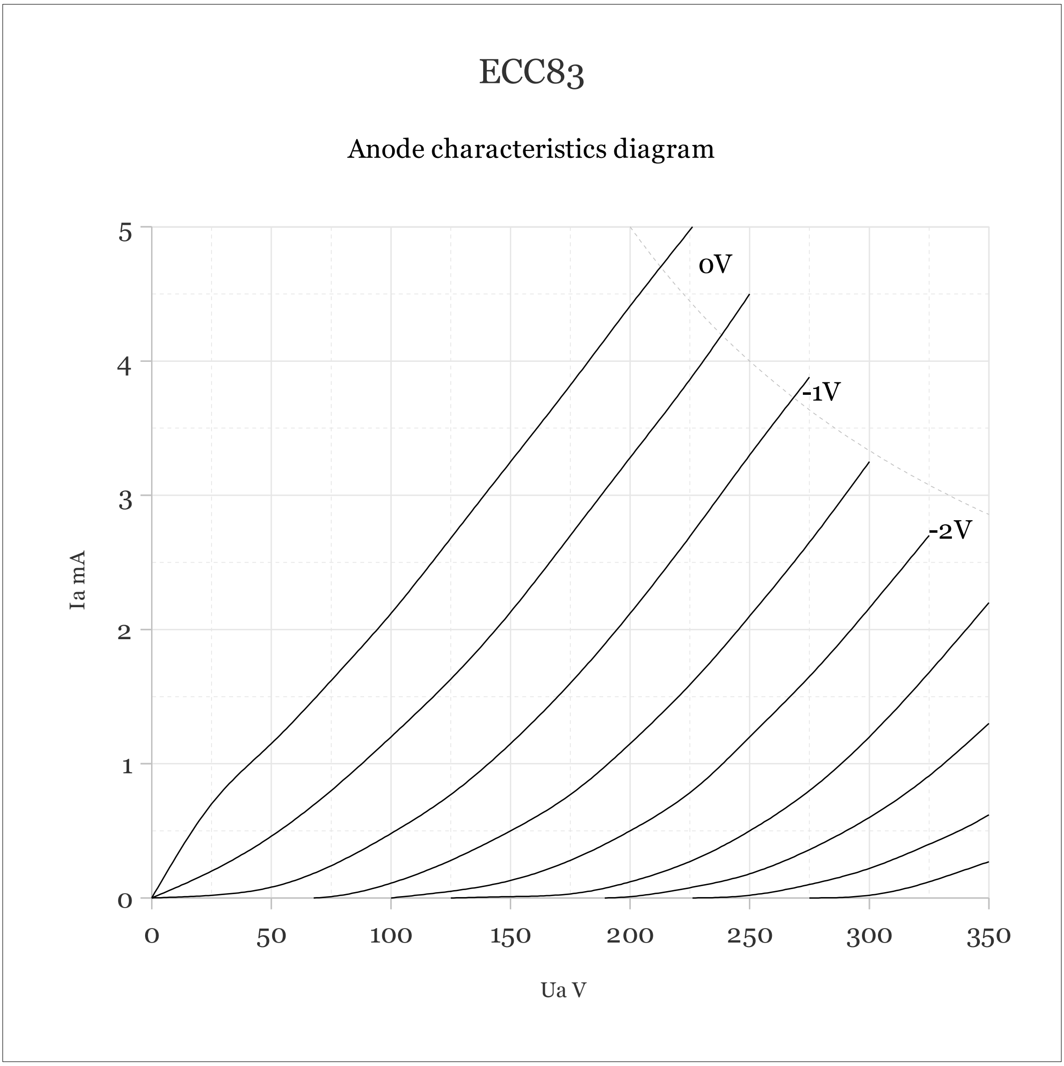
[5] Bell Labs. (1948) Press conference
[6] Okasura, S. et. al. (1994) History of electron tubes
[7] Jones, M. (2012) Valve Amplifiers
[8] Williamson, D. T. N. (1949) Design of Tone Controls à Auxiliary Gramophone Circuits
[9] Jones, M. (2004) Building Valve amplifiers

8 Appendix

8.1 A – Anode characteristics diagrams

8.1.1 A1

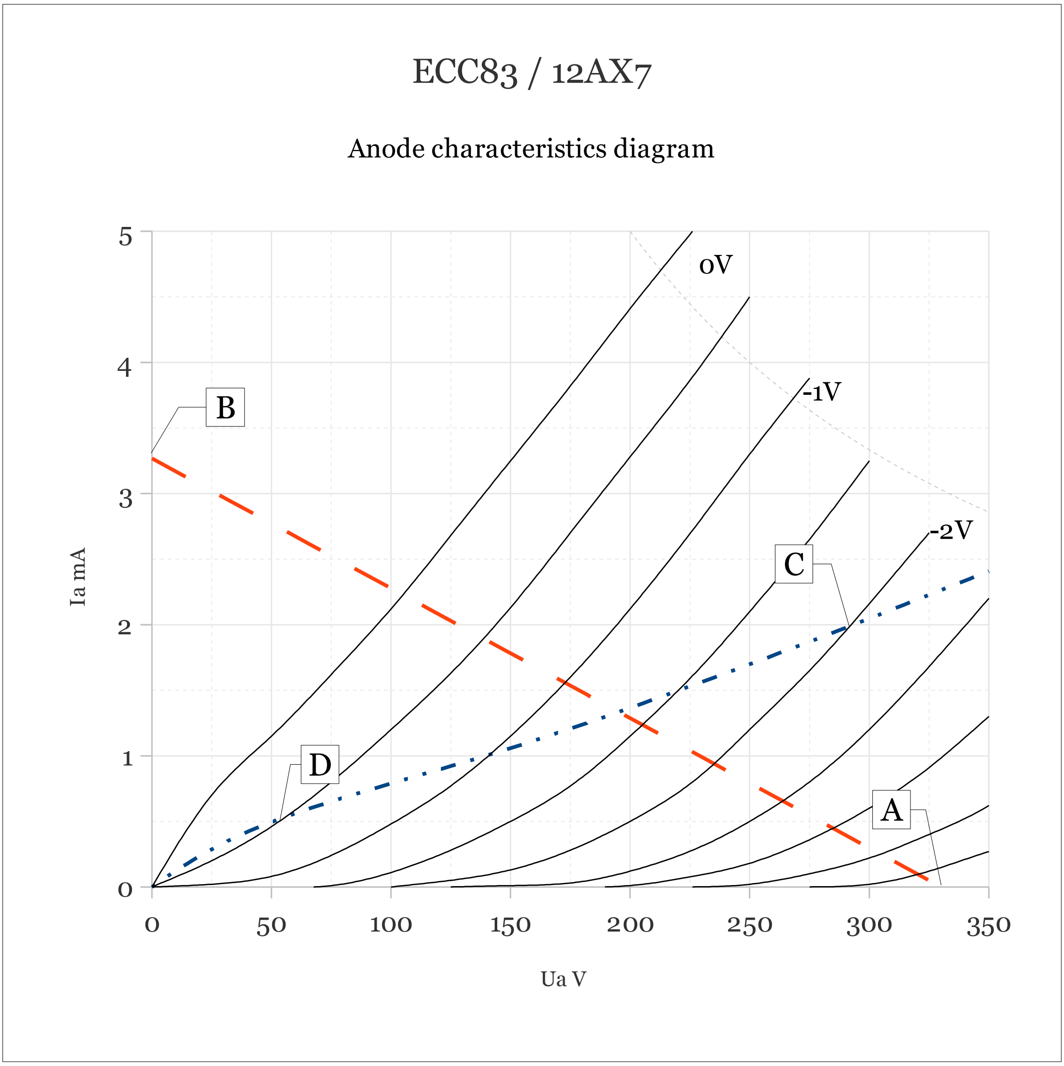
A digital version of a static anode characteristics diagram.



The anode characteristics diagram of the EBC91 triode, one of the two triodes in an ECC83 electron tube.

8.1.2 A2

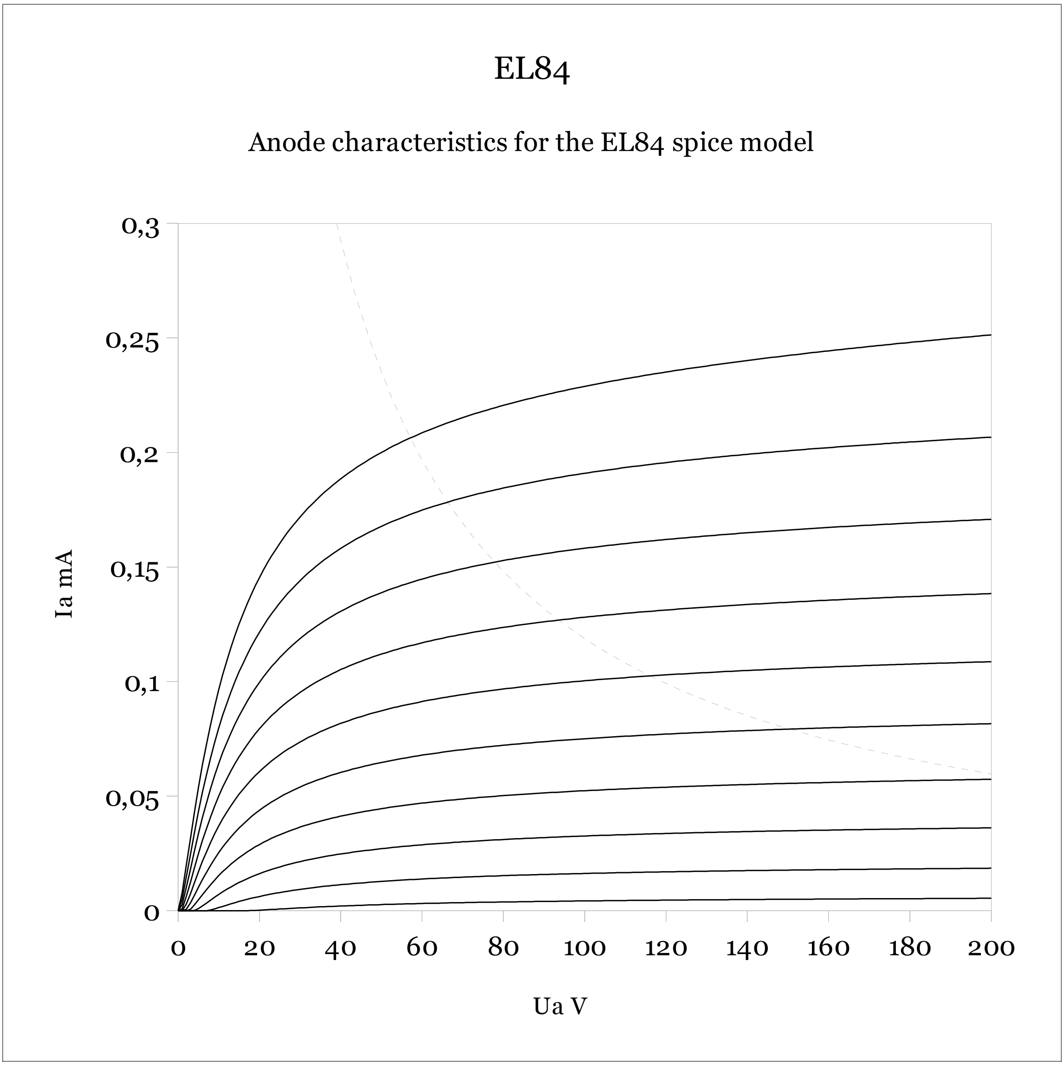
Examplified loadlines of a ECC83 grounded cathode gain stage.



The dashed red line is a anode loadline and thr dashed dotted line is an exemplified a cathode load line of a EBC91 triode.

8.1.3 A3

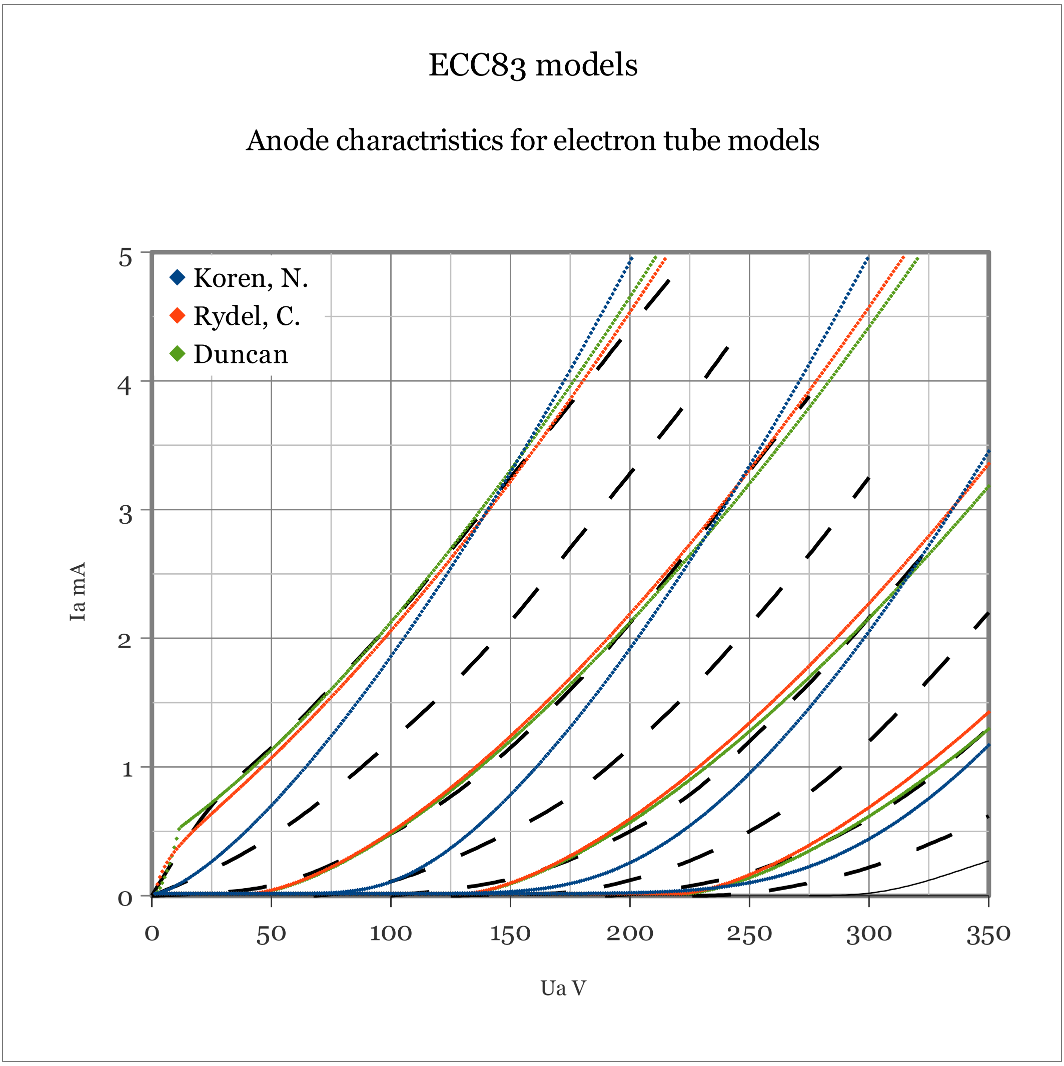
The EL84's static anode characteristics diagram is rendered in LTspice by the use of Rydel's EL84 model.



The anode characteristics for the Rydel EL84 model used in this paper. The curved lines are the control grid voltage for different bias levels on the control grid.

8.1.4 A4

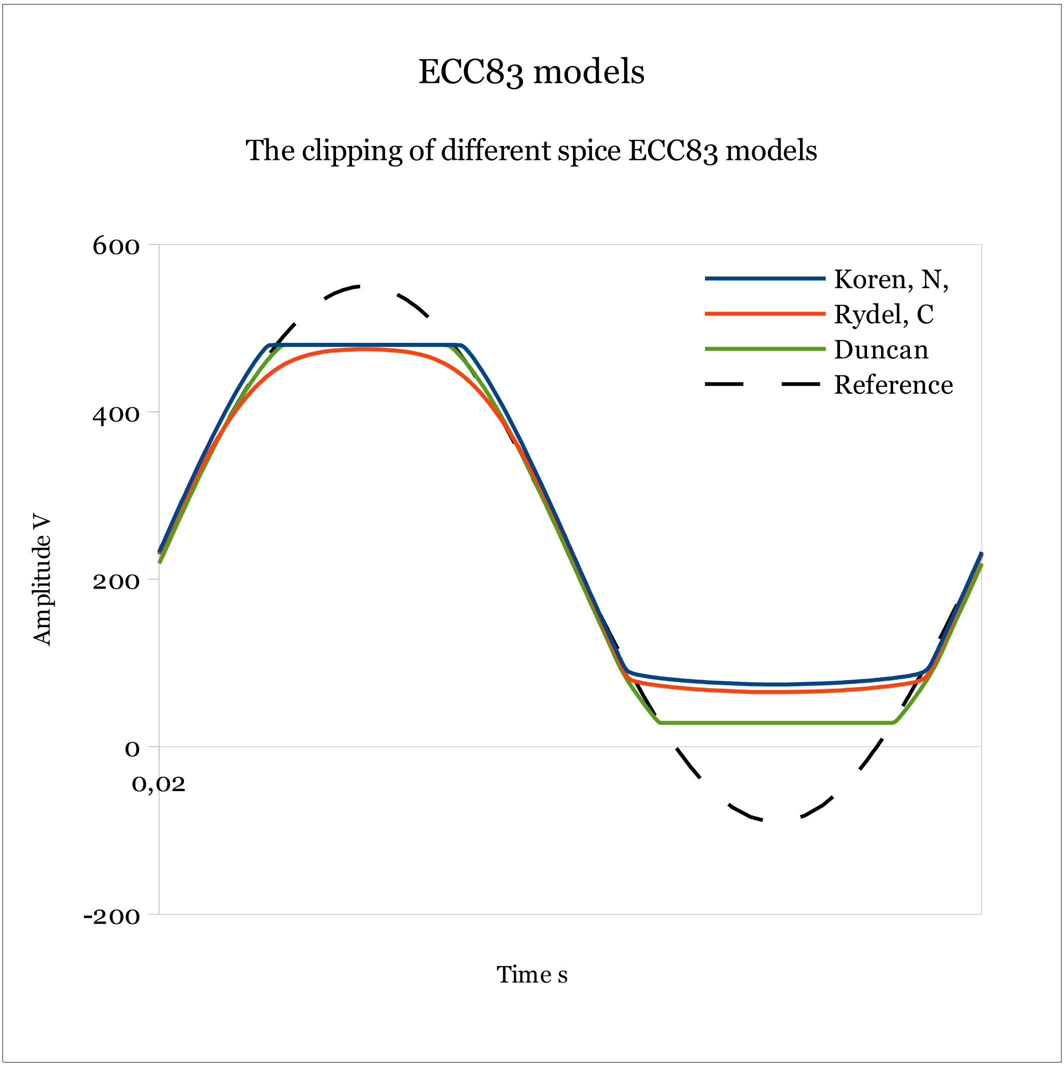
Static anode characteristics for the ECC83 spice models tested.



The anode characteristics for the ECC83 models tested in this paper compared with the dashed lines from the static anode characteristic diagram. The tested electron tube's grid voltage is incremented by -1 to prevent the plot from being to bloated.

8.1.5 A5

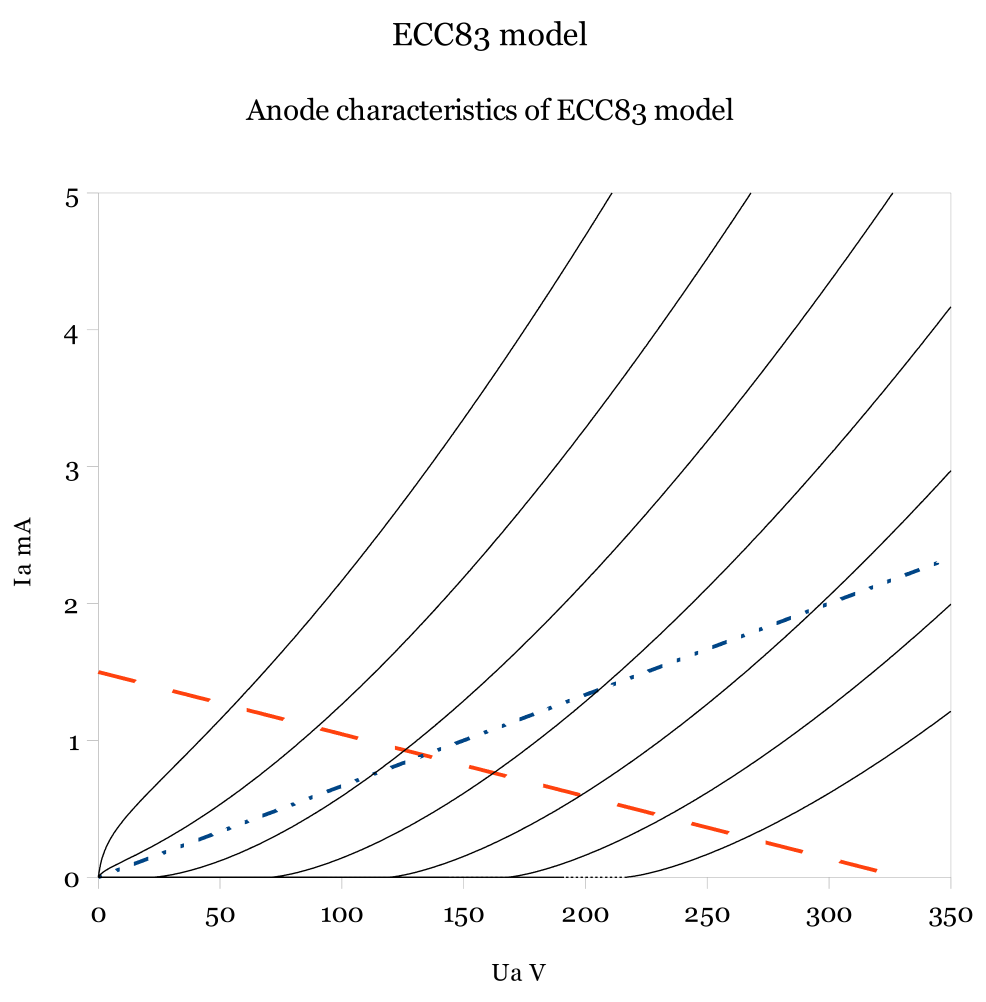
Clipping in spice electron tube models.



The ECC83 spice models are pushed into clipping. Notice how the tube models mimick clipping in real electron tubes. Clipping in real electron tubes are soft, e.i. no hard edges in the out signal.

8.1.6 A6

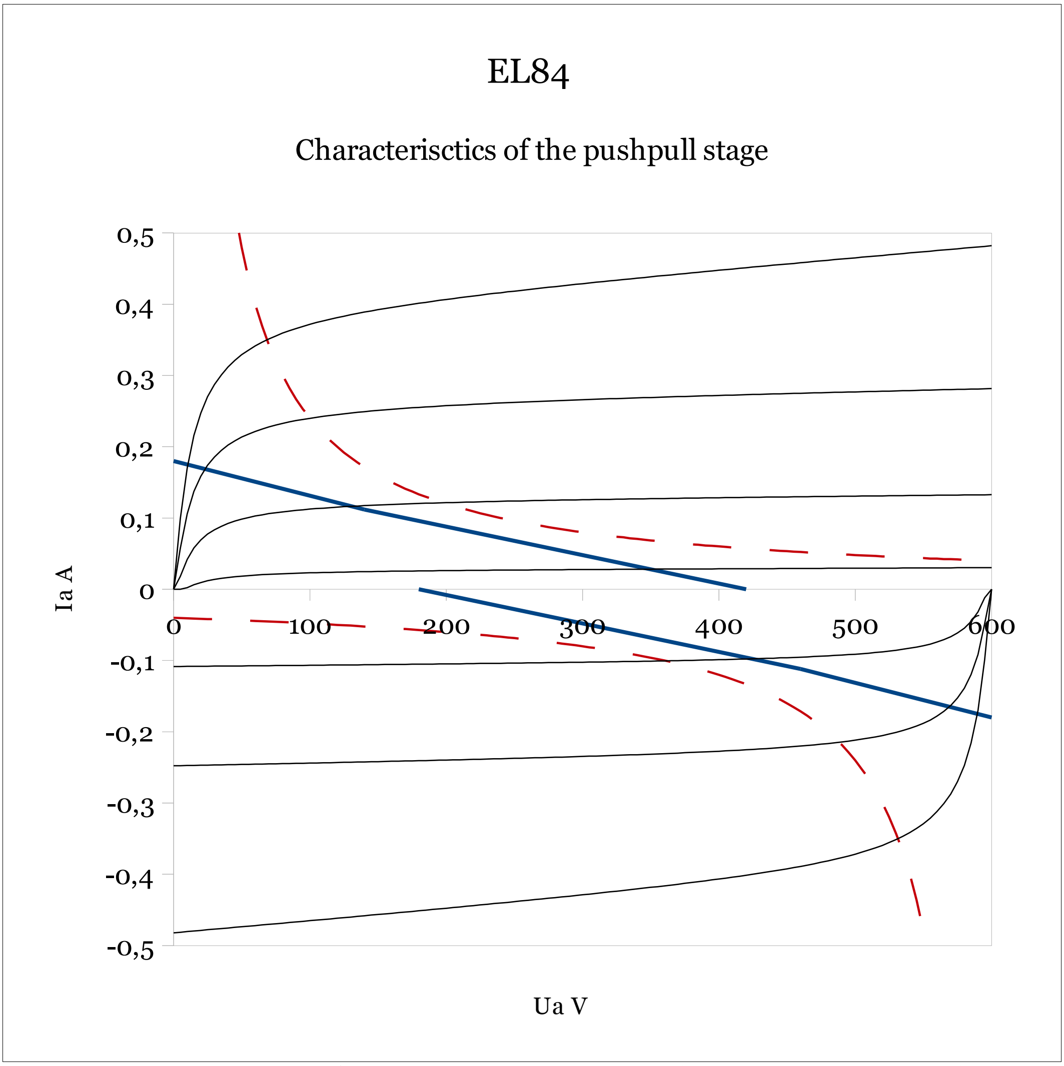
Loadlines for the modeled grounded cathode gain stage.



The anode and cathode loadlines shows where the bias point of the modeled grounded cathode gain stage is.

8.1.7 A7

The loadlines for the power tubes in the output section.

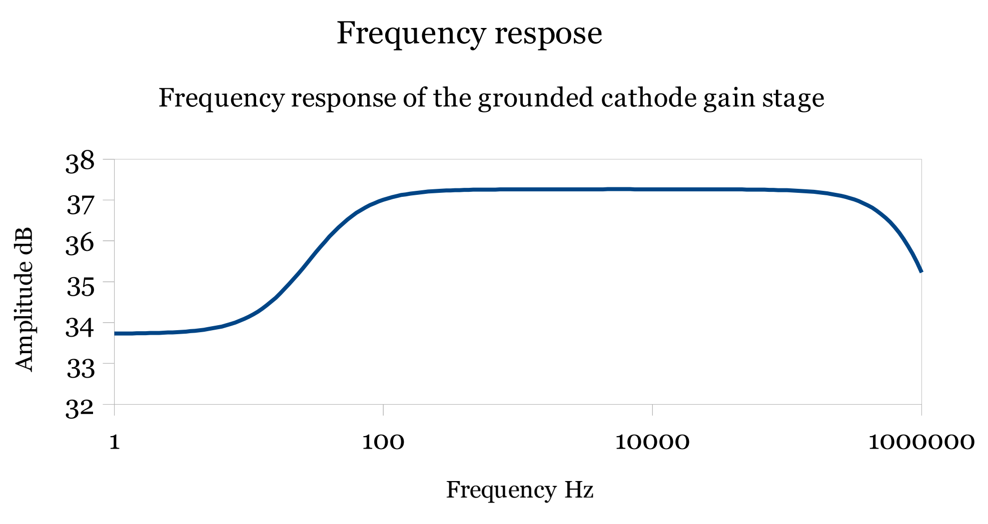


The anode characteristics of a pushpull power stage wit h4 EL84 pentodes. The blue bold lines are the loadlines of each side of the power stage.

8.2 B – Frequency responses

8.2.1 B1

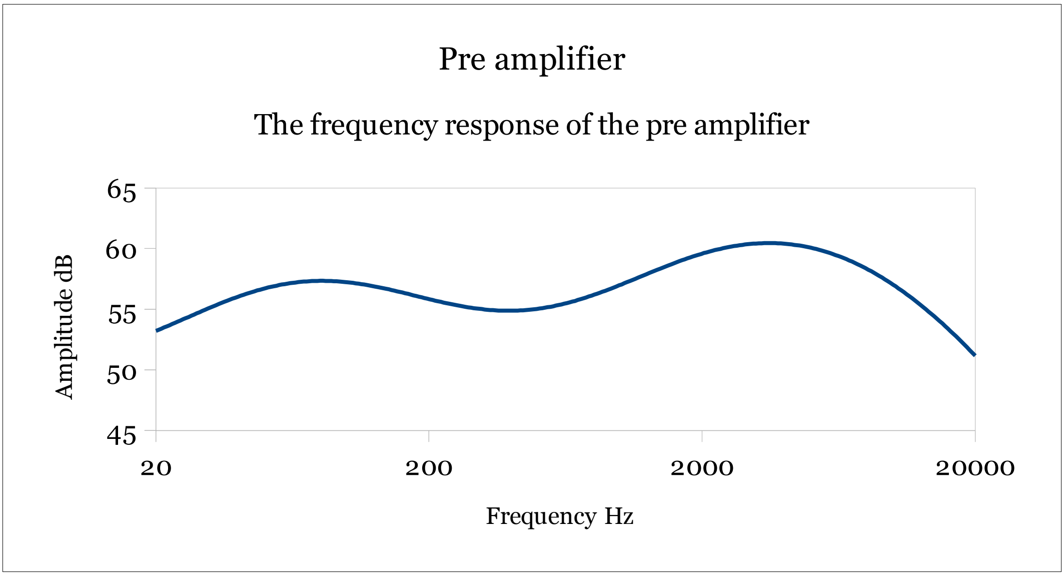
The frequency response of the grounded cathode gain stage modeled in LTspice.



The frequency response of the simulated grounded cathode gain stage.

8.2.2 B2

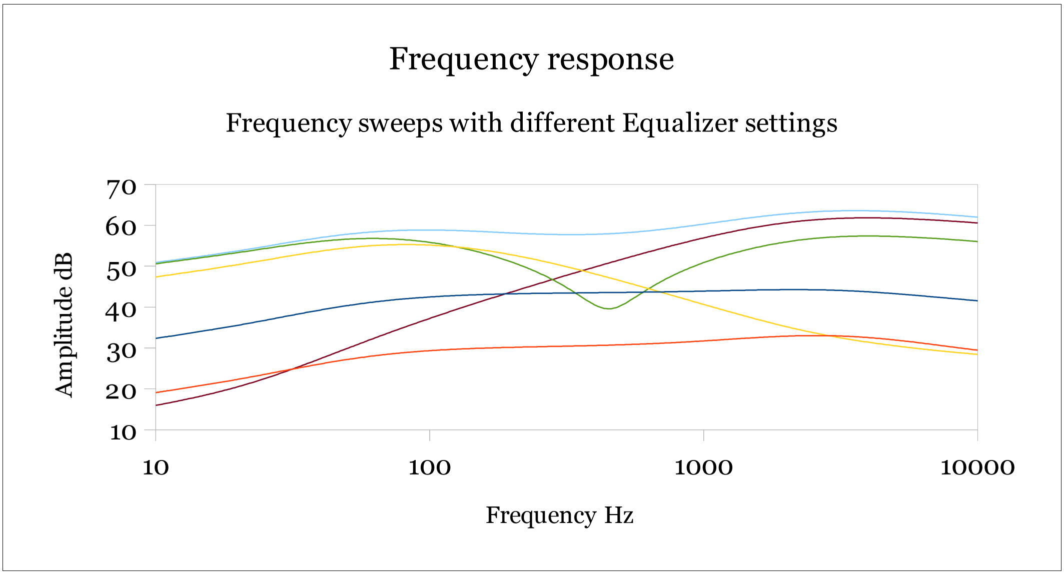
The frequency response of the pre-amplifier modeled in LTspice.



The frequenvy response of the pre amplifier. The freqency response reveals two bumps, one in the bass range and one in the treble range of the spectrum.

8.2.3 B3

The frequency response for the amplifier with different tone stack settings.

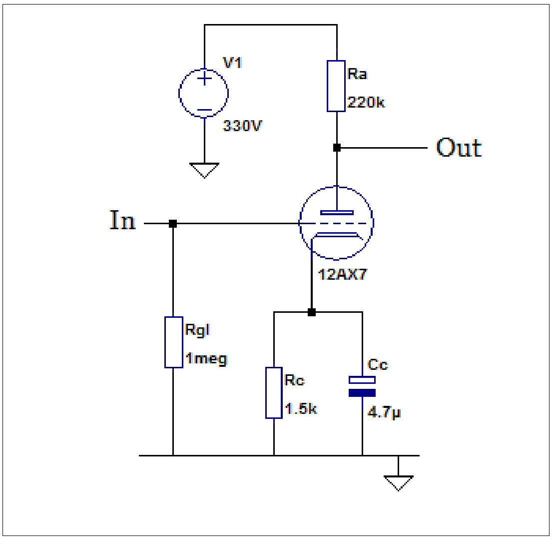


Frequency response of the amplifier. Different tone stack settings is used to check that the attenuation of different frequency intervals are somewhat similar. The volume control is set to 8 in all sweeps.

8.3 C – Circuitry

8.3.1 C1

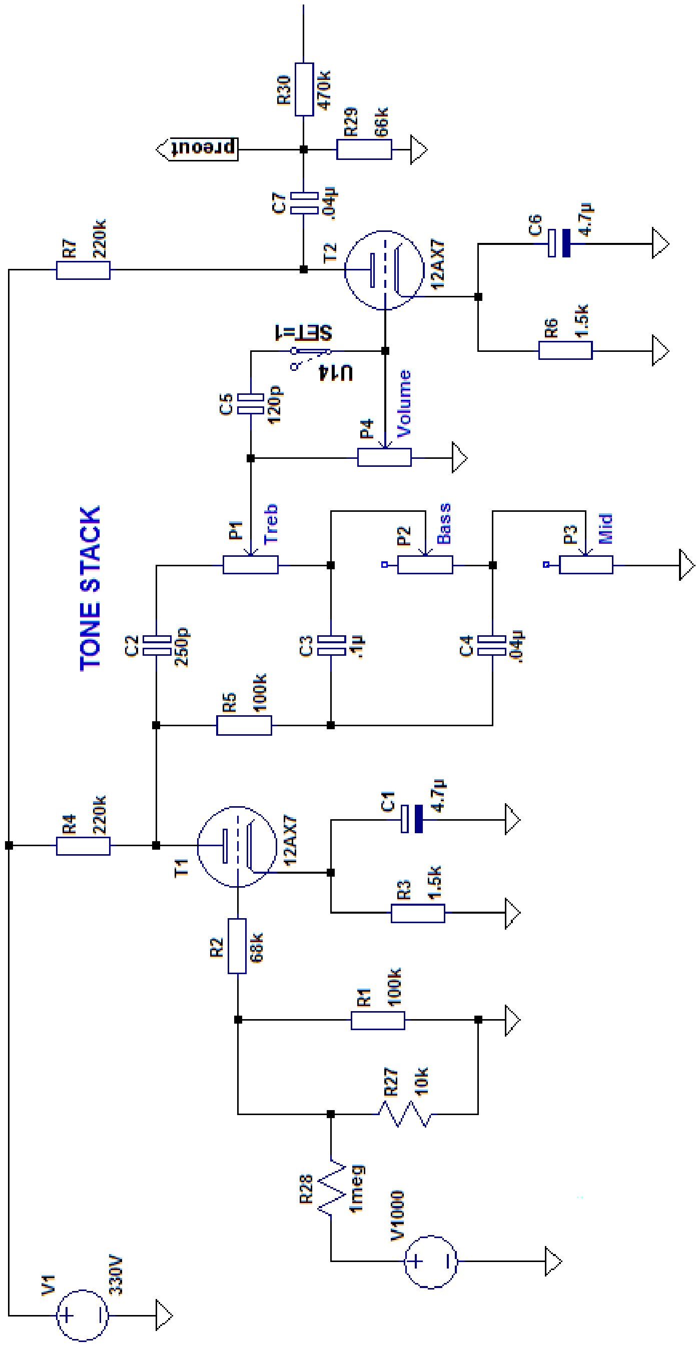
The grounded cathode gain stage as it is modeled in LTspice.



The grounded cathode gain stage set up from the LTspice simulation.

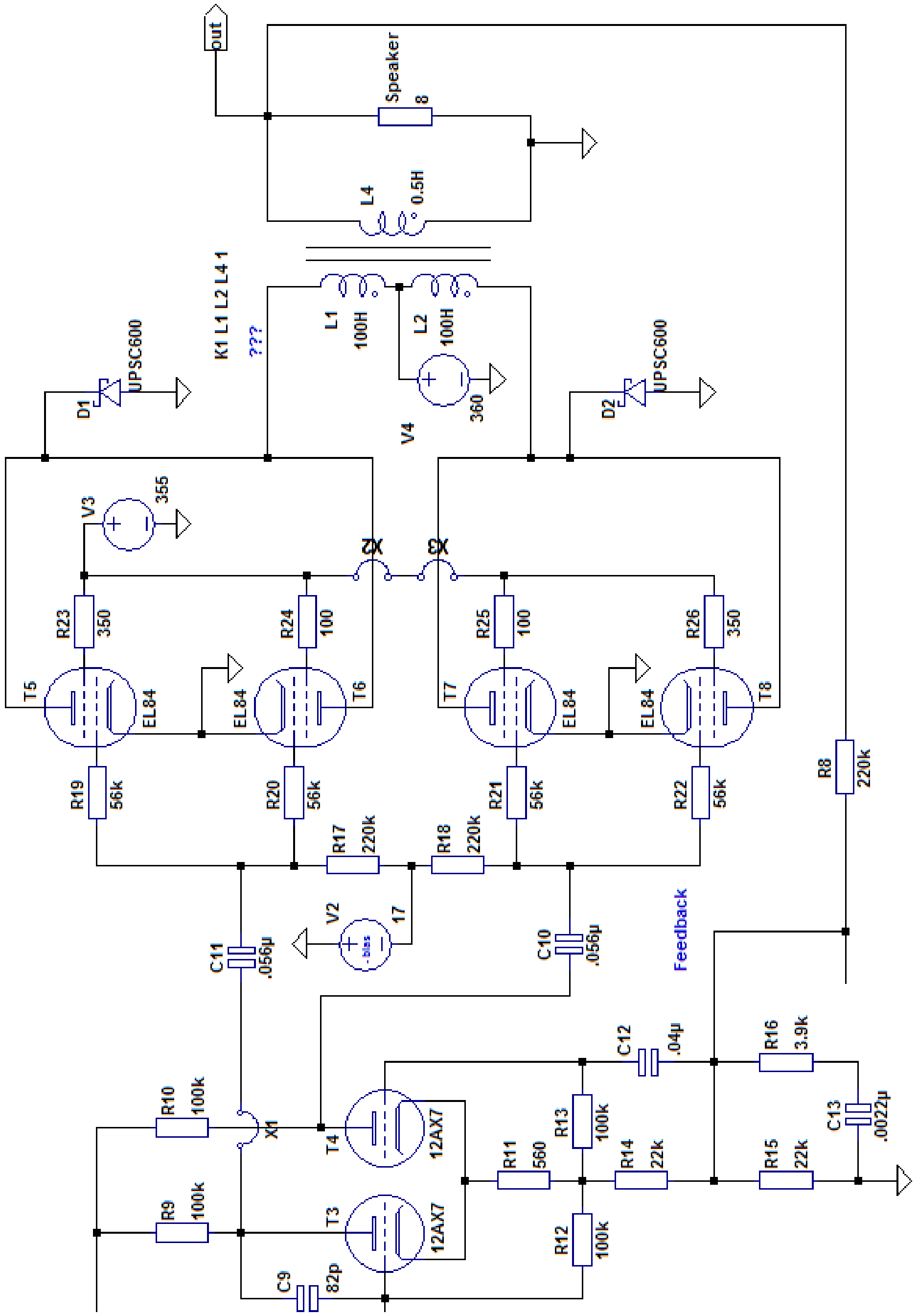
8.3.2 C2

Pre-amplifier modeled in LTspice.



8.3.3 C3

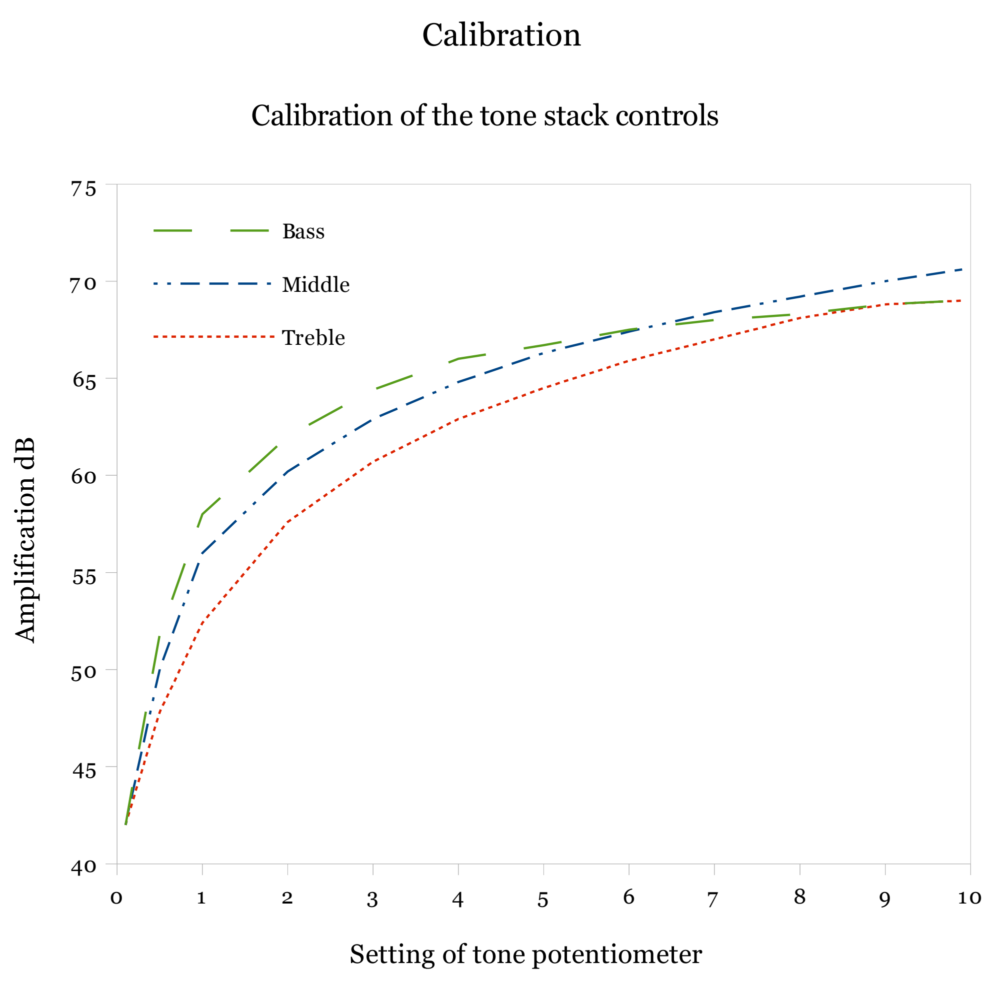
Power section modeled in LTspice



8.4 D

8.4.1 D1

The calibration of the tone controls in the tone stack.



The calibration of the tone stack. The amplitude interval of all three frequency bands are of the same magnitude, 40 to 70 dB. The potentiometers for this set up is, bass = 250 kΩ, middle=50 kΩ and treble=100 kΩ.