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Low Voltage Vacuum Tube Pre-Amplifier for Guitar

From User Needs to a Commercialized Product

Master of Science Thesis

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Göteborg, Sweden, 2011

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Cover:
Prototype of a distortion sound effect for guitar implementing a low voltage vacuum tube pre-amplifier

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SUMMARY

The vacuum tube was the first electrical signal amplification device. The solid state transistor, upon its invention, replaced the vacuum tube in most applications. Vacuum tubes, however, are still commonly found in guitar amplifiers due to their aurally pleasing non-linear behavior. Vacuum tubes require high voltages to operate properly; low voltage operation leads to extreme non-linearity which is not aurally pleasing. The high voltages necessary for proper operation have limited the use of vacuum tubes in guitar distortion sound effects due to the high costs associated with high voltage operation.

In what was identified as a price sensitive market, opportunities were present to introduce products, including distortion sound effects, which can implement vacuum tubes at prices which are competitive with solid state devices. In order to leverage these opportunities, a concept needed to be developed for improving the linear behavior of the vacuum tube under lower voltage operation.

A technical background study was performed to gain an understanding of the technical cause of the program and in order to be able to map electrical signal properties to sound characteristics. A market analysis was performed to confirm feasibility and identify specific market opportunities. A user needs study was performed to assess the needs of different market segments. The product of the user needs study was a list of design requirements. These design requirements were used as a decision making tool as concepts for potential circuits and other product considerations.

Using the design requirements as a guideline, a circuit was designed implementing an attenuated input using a capacitor based voltage divider, in conjunction with a pull-up grid-leak bias resistor which would theoretically improve the linear behavior of the vacuum tube under low voltage operation. A distortion sound effect was designed implementing this circuit and a prototype was created. User testing of the distortion sound effect confirmed the improved linear behavior compared to conventional low voltage vacuum tube circuits. User testing identified undesirable distortion content and unresponsive volume control. The design was iterated to incorporate a lower anode resistance and a logarithmic volume control. A second prototype was constructed implementing these design changes.

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Keywords: Vacuum, tube, low, voltage, pre-amplifier, guitar, distortion, linearity

Contents

1 Background

1.1 What is Audio Distortion

Distortion, in its most general sense is simply an alteration. In audio applications, distortion is generally cause by an electronic signal being altered, either intentionally or unintentionally, by some components in a signal path. In almost every instance, distortion is considered undesirable, and many products have design considerations to minimize distortion. In audio applications, however, this is not always the case. In music, particularly blues and rock music, distortion can be desirable; it has largely shaped the sound of several genres of music for decades. It is extremely common to intentionally distort a signal to affect its sound quality, and a whole industry thrives on providing devices to distort audio signals.

1.2 What Causes Audio Distortion

There are several sources of audio distortion in electric guitar applications. One extremely common form of distortion is speaker distortion, in which the speaker itself cannot accurately convert the electrical signal into sound waves, creating a slightly distorted output. Signals often become distorted when component power supplies cannot provide enough power to produce a signal accurately; this often occurs in output transformers which connect amplifiers to speakers, and in power supply circuits for a specific few guitar amplifiers. The most common form of distortion, however, comes from an amplifier itself.

In general, there are two amplification methods used in electric guitar, the vacuum tube and the solid state transistor. Both technologies provide distortion that is generally caused by signal clipping, but each technology produces drastically different sounding distortions. The first method of amplification was the vacuum tube. Vacuum tubes were initially used in amplifiers simply because they were the only technology available. When driven with a strong enough input signal, a vacuum tube cannot accurately produce a strong enough output signal. Figure 1 illustrates what this phenomenon looks like. The dashed line represents a signal threshold or maximum signal that the vacuum tube can reproduce. Any signal outside of this threshold will be “clipped” by the threshold. We can see that vacuum tubes do not simply chop the signal off sharply, and that the signal still has rounded edges. This is referred to as “soft-clipping.”

Solid-state transistors began appearing in the guitar amplification market in the early 1960's, offer lowering prices and smaller product size. Much like vacuum tubes, solid state also can only reproduce signals up to a certain threshold. The major difference between the two is what happens after this threshold is crossed. Figure 1 illustrates the distortion phenomenon in solid-state devices. We can see that much like the vacuum tube, the output signal is clipped by the threshold, but the clipping is much sharper, creating an output signal which is more like a square wave than a sine wave. This is referred to as “hard-clipping.”

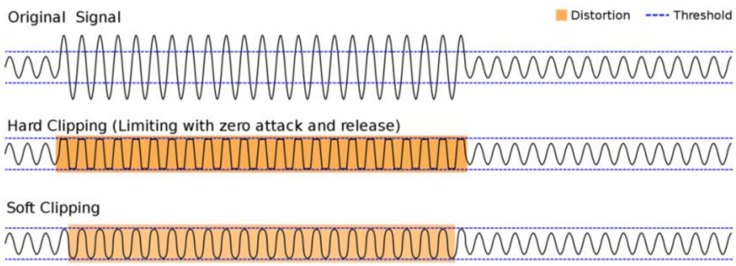


Figure 1: A comparison of "hard" and "soft" clipping

The quality and amount of distortion caused by the “soft-clipping” of vacuum-tube guitar amplifiers is generally preferred by musicians, and considered to be “warm” and musically pleasing. (Doidic, Mecca, Ryle, & Senffer, 1998) These devices offer a region of linear response, providing an undistorted sound, and a region of distorted response, with increased harmonic content. It is generally believed that having a controlled amount of distortion available when desired is more pleasing to the human ear and has a richer, fuller tone. This controlled amount is referred to as “feel” or “touch sensitivity”, allowing a user to control harmonic content by controlling the strength of the input signal. (Kawakami, 1991) Due to these aural advantages, vacuum tubes are widely used in guitar amplification despite having higher significantly higher costs, requiring heavy transformers to operate and having lower reliability than solid state devices.

While many amplification circuits on the market simply offers solutions that are large and expensive, attempts have been made to deal with these problems. Products have been developed that use a variety of novel methods to provide high voltage to vacuum tubes. These efforts have lowered product size, weight and cost, but not to the level of solid state devices. Products have also been developed that operate vacuum tubes at low voltages, often called “starved-plate” operation. By limiting operation of vacuum tubes to low voltages, the vacuum tube is only operating in the most non-linear response range, losing the advantages of the linear range of operation. In this operation, small signal changes correspond to large changes in output, leading to an uncontrolled “touch sensitivity”, and consequently an uncontrolled output. This uncontrolled output goes well beyond the range of linear operation, producing an overly distorted, unpleasant sounding output.

1.3 Common Vacuum Tube Applications

Figure 2: A vacuum tube guitar amplifier

Although vacuum tubes were at one point prevalent in many products, they are now mainly found in two applications: guitar amplifier and guitar sound effects. Guitar amplifiers generally consist of at least two separate circuits, a pre-amplifier and a power amplifier. The role of the pre-amplifier is to amplify the low voltage output signal to a line-level signal which is strong enough to drive the power amplifier. The power amplifier then receives the signal and further amplifies it in order to drive a loudspeaker. The pre-amplifier, power amplifier and loud speaker may be housed together or separately based on the application, and multiple stages of pre-amplification or power amplification may often be present in a single device. Vacuum tubes are most common in the pre-amplification stage. Vacuum tubes are much less common in power amplification stages as their output impedance is significantly higher than that of the loudspeaker it is feeding. (Berning, 1997)

Figure 3: A vacuum tube distortion effect

Sound effects units are a very broad range of devices which are added to a signal change to alter the signal and thereby the eventual sound. Although this category is very broad, there are some similarities between almost all sound effects unit; they all work with small input signals and almost all use some form of pre-amplification. For many sound effects, the pre-amplification should be completely accurate, making a solid-state pre-amplifier ideal. This isn’t the case for the most commonly used sound effect, the distortion effect. These devices are essentially stand-alone, high distortion pre-amplifiers. Vacuum tubes are often found in distortion effects for their pleasant aural characteristics and touch sensitivity.

1.4 Vacuum Tube History and the Diode

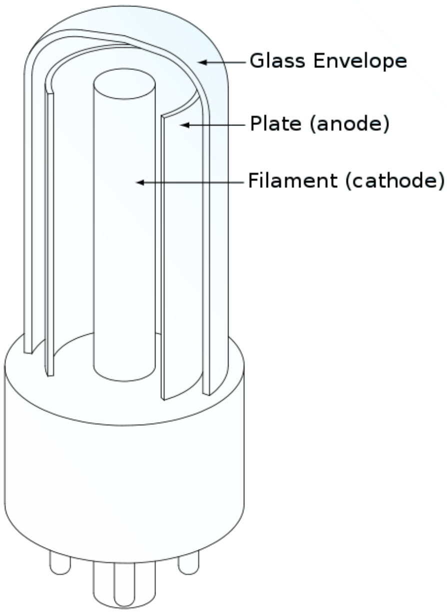


Figure 4: Section view of a vacuum tube diode

When a metal cathode is heated in a vacuum, it experiences a form of thermionic emission, emitting electrodes into the vacuum; this is known as the Edison Effect (although initially discovered by Frederick Guthrie in 1873.) In 1904, John Ambrose Fleming invented a device which was essentially a heated cathode and a positively charged anode in an evacuated tube. Electrons would only flow from the cathode to the anode, essentially only allowing current to pass in one direction. This device was then known as the Fleming valve, but later would come to be known as the diode for its two electrodes. (Tyne, 1994)

1.5 The Triode

Three years after the invention of the vacuum tube diode, Lee De Forest filed a patent for a new vacuum tube device. The new device contained a third electrode between the filament and the plate. He found that by varying the voltage in the new electrode, he could vary the flow of electrons from the filament to the plate. In 1919 this device was named the triode, for its three electrodes. At the time it was by far fastest and most accurate signal switching element available at the time. Initially applications of the triode suffered from a non-linear, distorted amplification at low volumes. Engineers characterized the behavior of the triode and found that the distortion was only associated with a certain range of operation. In order to operate in this range, they found that they had to applying a negative voltage (bias) to the grid, to center its operation in the linear region. This was originally accomplished by applying a dc voltage from an external source, often a battery, directly to the grid. This is now known as grid biasing. Since then, many other biasing techniques have been developed. (Tyne, 1994)

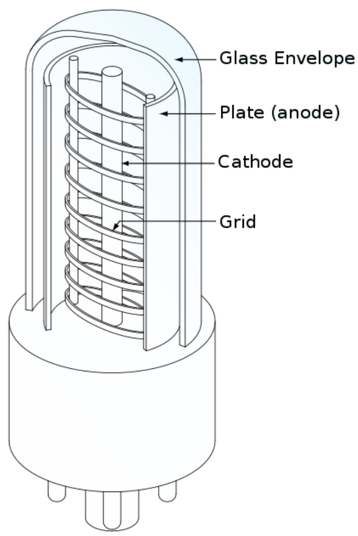


Figure 5: Section view of a vacuum tube triode

1.6 The Tetrode

Although engineers at the time were able to solve the distortion problems of the triode, they were unable to find a solution to another problem; triodes, often employed in radio equipment, would pick up high voltage oscillations. The source of this noise was identified as capacitance between the positive anode and negative grid across the vacuum between them. In 1926, a solution was devised to simply screen from the output by inserted another positive element between the anode and the grid, and to send the intercepted oscillations to ground. This fourth electrode was named the screen grid and the device employing was named the tetrode for its four electrodes. While the tetrode did solve the high frequency noise problems of the triode, it introduced a new problem. Electrons emitted by the cathode travel so fast that they knock electrons loose from the cathode upon impact. This phenomenon is known as secondary emission. In a triode, the secondary two leads to a small range where plate current decreases with plate voltage (the response of the vacuum tube is negative.) This embodies itself as a negative kink in the graph of plate voltage against plate current, known as the tetrode kink. (Tyne, 1994)

1.7 The Pentode

Two years after the introduction of the tetrode, the pentode was introduced. The pentode inserted a fifth electrode between the anode and the screen grid. This grid was biased negatively to suppress the secondary emission from reaching the screen grid. This grid was named the suppression grid, and solved the problem of the tetrode kink. In general, pentodes offer lower feedback capacitances, worse noise performance, higher efficiency and better resilience to changes in supply voltage than triodes. All of these facts make the pentode very well suited to higher power applications. (Tyne, 1994)

1.8 Technical Background

The effective cathode voltage of a triode vacuum tube can be expressed as the following (Maxwell, 1871):

$$V_{eff} = V_g + \frac{V_p}{\mu}$$

Where V_{eff} is the effective cathode voltage, V_g is the grid voltage and V_p is the plate voltage. Rearranging this, we can see that the plate voltage is equal to the difference between effective cathode voltage and grid voltage times µ. The µ term is the amplification factor, a simple value which relates plate voltage to cathode voltage and grid voltage. Amplification factor is not constant, however. Maxwell found it to be a function of the geometry of a vacuum tube, expressed as (Maxwell, 1871):

$$\mu = \frac{-2\pi d_{gp}}{a \ln\left(2 \sin \frac{\pi r_g}{a}\right)}$$

Where a is the distance between grid wires, d_{gp} is the distance between the grid and the plate, and r_g is the radius of the grid wires. This holds true, but only under certain conditions assumed by Maxwell. Maxwell assumed that the grid wires are small compared to their spacing, that the electrodes are infinite and have no edge effects, and that the distance from the grid to the cathode is at least equal to grid pitch. The first assumption is true, grid wires are usually small compared to their spacing. Although not true, the second assumption does not affect the model much; edge effects are present, but are small enough to ignore in theory. The third assumption, however, has some major effects on vacuum tube behavior. When the distance from the grid to the cathode is smaller than the grid pitch (grid wire radius over grid wire distance), individual wires have an effect on the cathode, and a non-uniform field is created between the grid and the cathode. As the grid increases towards cut-off potential, it pulls harder and harder on the plate, creating a stronger and stronger electric field. The series of images of Figure 6 shows the progression of the electric field as the grid becomes more negative (input signal increases from right to left) with respect to both the cathode and the plate.

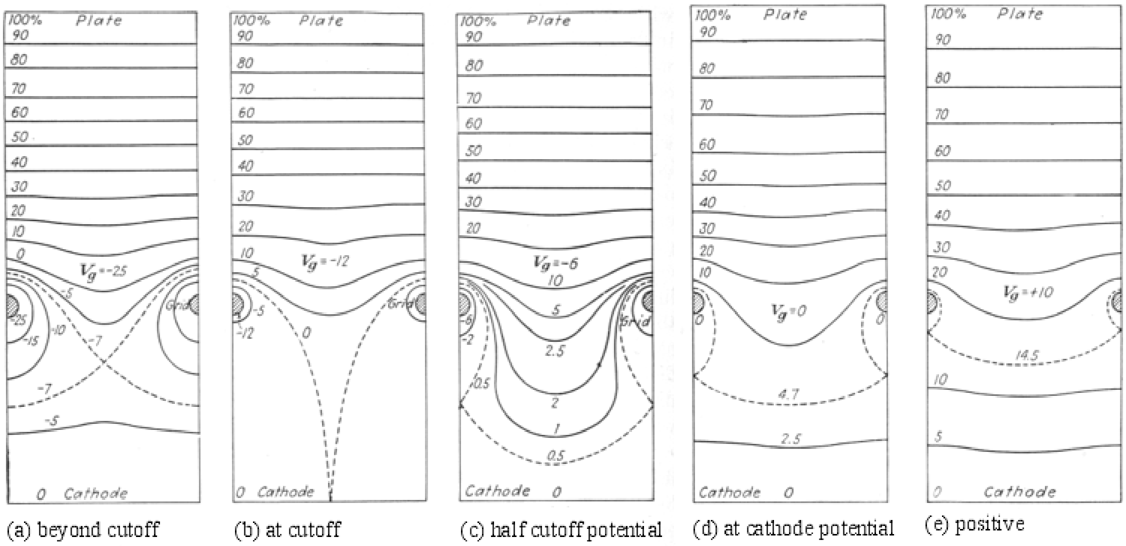


Figure 6: Electric field at several grid voltages (Harper, 2003)

Here we can see as the grid voltage gets more negative, there is a stronger electric field between the grid and the cathode. What are the effects of this, though? The electric field essentially blocks part of the cathode (or cuts it off, hence the term “cut-off”). This effect is also called “inselbildung”, which is German for island, creating an island of effective cathode surrounded by a sea of ineffective cathode. (Fremlin, 1939) Figure 7 illustrates this effect, as the cathode progresses from fully effective to fully cut off.

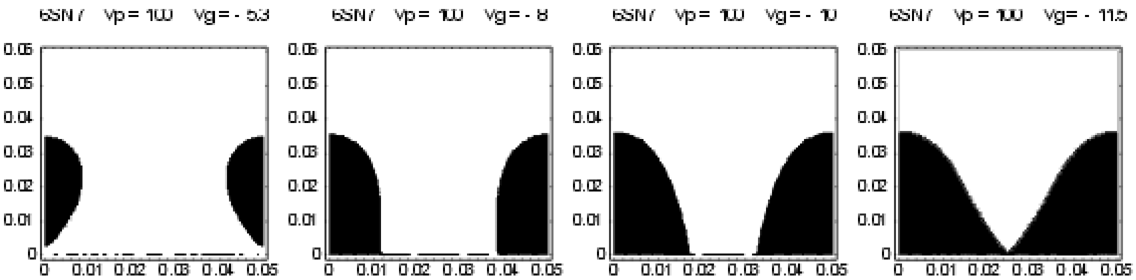


Figure 7: Inselbldung effect (Harper, 2003)

As stated earlier, the effects become more drastic as grid pitch increases beyond grid to cathode distance, and as grid voltage raises relative to plate voltage. We can clearly see the difficulties with low plate voltage operation. Furthermore, many modern tubes work contain small grid spacing, leading to high grid pitches, only exacerbating the problem.

Faced with the problem of the electric field of the grid blocking the cathode from proper operation, one would naturally think that the obvious solution is merely to bias the grid positively. As can be seen in Figure 6e, this indeed would remove the non-linearity due to cut-off. Unfortunately, having a positive grid causes its own problems. A positive grid in the path of electrons will naturally attract the electrons. This causes the grid to conduct a grid current, which essentially consists of electrons which were intended to be sent to the anode. These stolen electrons are a source of non-linearity. The range of linear operation is essentially set, limited by grid conduction on one end and cut-off on the other. (Rutt, 1984)

We now have an idea of why the triode is non-linear. While a theoretical model is useful in wrapping our minds around the problem, practical data may be more suitable to characterizing and solving the problem. The graph below shows the response of amplification factor to plate voltage of one 12AX7 triode.

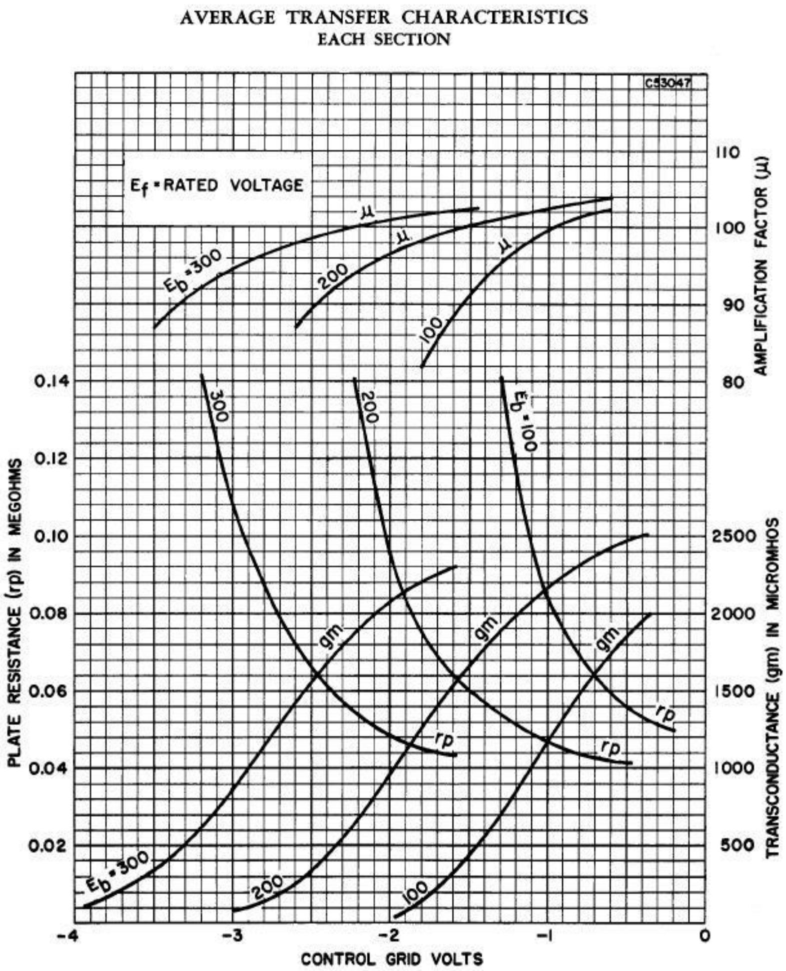


Figure 8: Effects of plate voltage on amplification factor (Sylvania Electronics Products Inc, 1955)

Figure 8 contains three separate plots, each representing a different plate voltage. We can see that at lower plate voltages the changes in amplification factor are more extreme for given changes in grid voltages, corresponding to less linearity. The curves for higher plate voltages also have a large range of grid voltages where the amplification factor curve is fairly flat, corresponding to a linear region of response, also known as headroom. We can now see how the theory is embodied in practical application, as lowering plate voltage towards grid voltage leads to greater non-linearity and a loss of headroom. The shape of the 300V and 200V plate voltage curves correspond to operation that is generally considered aurally pleasing. As we drop to 100V the non-linearity is already becoming extreme, and there is no headroom. Very low voltages correspond to a complete loss of linearity, and many products operating at these very low voltages are considered to have poor sound quality.

In sum, this non-linearity is inevitable in the operation of vacuum tubes; it is present in theory and embodied in practice. When operated at its rated voltage, the vacuum tube's non-linearity is considered aurally pleasing. When operated at lower voltages, however, the change in response happens too quickly for the user to control, and the non-linearity is too extreme, creating a sound that is no longer aurally pleasing.

2 Purpose

Vacuum tube based guitar sound effects and amplifiers are expensive, large and heavy due to high operating voltage of vacuum tubes. Low voltage operation of devices that are intended for high voltage leads to low headroom and uncontrolled distortion, stemming from a non-linear response region that is both extreme and spans a wide operating range. This can lead to unpleasant harmonics, lack of touch sensitivity and an undesirable sound. Due to this fact, most products on the market use solid-state amplification, which provides a decidedly less desirable sound character. The purpose of this project is to develop a pre-amplification circuit that operates at low voltages while obviating the non-linearity associated with this operation. Furthermore, the purpose of this project is to implement this pre-amplification circuit into a distortion sound effect for guitars, to be sold on the consumer market.

3 Objectives

In order for the project to fulfill its purpose, the following objectives have been formulated:

- Study the background of the product and technology
- Analyze the technical aspects of the problem
- Understand the current state of the market
- Predict the future state of the market
- Identify the needs of users and other parties of interest
- Form working relationships with key users, suppliers and retailers
- Develop a set of design requirements to translate user needs into design parameters
- Functionally decompose the product
- Generate a breadth of concepts for functional solutions
- Objectively select which concepts best fulfill the design requirements
- Create detailed designs of selected functional solution concepts
- Manufacture a prototype of the design
- Present prototypes to key users for testing
- Iterate the design to a final design based on user feedback
- Modify the prototype to incorporate the iterated design
- Create an exploration plan
- Address intellectual property concerns

4 Methodology

4.1 Strategy

The nature of the problem at hand was complex. Sound quality was both subjective and difficult to describe. As such, there were difficulties coming to conclusions about what users want, designing to these users desire and confirming that users would enjoy a finished product. In order to deal with these difficulties a very structured approach was taken to the project. Using a structured approach would create a clearly traceable link between the finished project and user needs. This would ensure that every phase would consider all of the knowledge produced in previous stages and that the final design would fulfill user requirements. Within this structure, objective methods were used in order to deal with the subjectivity and qualitative nature of sound. By mapping subjective, qualitative statements to objective quantities, concepts could be developed, compared and designed to consider these statements. The use of this strategy was motivated by and in many ways draws parallels to the principles of axiomatic design. (Suh, 1990) The principles of axiomatic design suggest the use of independent requirements having minimal information content with direct traceability to user needs in order to a systematic format for designing successful products in the face of subjectivity. While axiomatic design principles include many specific design tools, these tools were not explicitly used as a part of the design strategy. The general principles of systematic design, independent requirements and design traceability were used as general methods of dealing with the subjectivity of sound quality. Actual product development processes and tools were in large part based on the methods outlined by Ulrich & Eppinger. (Ulich & Eppinger, 2008) As the work performed was not only part of a product development project, but an academic work in product development, the use of the principles of axiomatic design and known, systematic development methods could also serve as the basis for conclusions and development of product development systems.

4.2 Benchmarking and Market Analysis

The first phase of the investigation was a benchmarking and market analysis study. The general goal of this phase of the project was to analyze the current state of the market and predict the future state of the market. A further goal of this phase was to confirm the feasibility and potential position for a new product on the market.

Benchmarking was performed by visiting retailer stores, retailer interviews, searching internet retailers and accessing information made publicly available by manufacturers. Large industry publications created for manufacturers and retailers were also used as sources of information. Benchmarking was presented using example products of the most successful products available on the market, including key product data. This method was selected as it provides a clear visual introduction to those unfamiliar with the product while providing an easy to read, uncluttered and graphic presentation. Furthermore, due to eventual findings of the importance of branding, it was deemed important to provide visual presentations of competing products to illustrate other branding strategies while explaining eventual branding strategies, while providing point of design comparison.

Several tools were used in the market analysis study. A PEST analysis is a study of the political, economic, social and technological factors which affect a given market. This analysis was performed in order to identify external conditions that could potentially affect the market. Historical trends of external conditions were examined along with the current state of these conditions in an attempt to not only understand the current state of the market, but to predict the future state of the market. The scope of the PEST analysis was global, in an attempt to identify potentially favorable and unfavorable markets throughout the world.

Market share availability is the product of several market forces and awareness of these forces can assist in identifying market positions which are opportune and stable. These forces are clearly documented and commonly used in market analysis. (Porter, 1979) An analysis using Porter's Five Forces was performed in order to assess the internal conditions of the market. Historical trends of external conditions were examined along with the current state of these conditions in an attempt to not only understand the current state of the market, but to predict the future state of the market.

4.3 User Needs Study

The second phase of the investigation was a user needs study. The aim of the user needs study was to find out what different parties of interest want and demand from the product to be offered, and to turn this information into a list of design requirements and a business model. A further aim of the user needs study was to gain knowledge concerning the purchasing behavior of both users and distributors.

A series of 20 interviews lasting an average of 30 minutes each served as the data collection methodology. This was suitable due to the very subjective nature of sound quality. Many terms to describe sound quality are very ambiguous, and often mean different things to different individuals. The long interview format allowed for follow up questions to try to clarify any ambiguities in answers and terminology. The long interview format was also perfectly suited for non-quantitative data collection, which was the goal of the user needs study. Furthermore, the relationships built with users during long interviews were very important in this stage of the product development process. Once key users are identified, it was important to maintain relationships to have them serve as product testers and possibly lock them in as eventual customers.

An interview guide was used in order to make sure that certain key information was obtained from the users. This interview guide served more as a checklist, as the goal of the interview process was to allow the user to lead the conversation and convey what information they felt was important. All interviews were held one-on-one. When possible, interviews were held at the interviewee's performance space to allow the interviewee to better convey information about their current equipment. This was especially important when trying to convey information about sound, which can often be very hard to describe. Efforts were made to try to get an appreciable number of both casual and professional users, as well as retailers, so that all potential parties of interest are represented.

The data received from the user needs study was reduced and sorted based on both subject and party of interest. This information was used to identify key design characteristics and form a set of design requirements. The design requirements, when possible, included metrics of measurement so that generated concepts can eventually be judged objectively. The quality of sound is somewhat objective, and certain properties are hard to quantify, making it impossible to use measurement metrics for such properties. Design requirements will also be given weights of importance to be used in concept scoring. These weights were derived from the user needs study.

4.4 Design

The third phase of the investigation was the design phase. Concepts were generated after an extensive technical background search had been performed in order to make sure all feasible technological solutions are considered. The product itself performs very few discrete, separable functions; as such, little functional decomposition was necessary. The product, and thus the design process were separated as follows: the vacuum tube to be used, the surrounding circuit and the enclosure and interfaces. Although all attempts were made to maintain a completely uncoupled design, the nature of the design is inherently coupled. Different vacuum tube topologies allow for different types of circuits inherently. As such, functional solutions have been designed in some sort of order. This necessary design order is a clear reflection of what is a coupled design, inherently violating the Independence Axiom of axiomatic design. (Suh N. P., 1998) This was mainly because the vacuum tube was a subcomponent of the circuit system. The vacuum tube selection process took place before the circuit design process in order to ensure that a suitable vacuum tube existed to operate in the conditions required for a given circuit.

The concept generation process itself was partially limited by available technology, especially in the area of vacuum tubes, where creating a new solution is simply infeasible. When possible, analogous fields were used as sources of concept generation. Circuit concepts, for instance, were often generated based on other non-linear devices and devices which aid in non-linearity. This is a known tool for incorporating knowledge from other fields. (Roy, 2004) Concepts presented using short explanations and graphical depictions, instead of a tabular format, in order to demonstrate the fundamental operating principles of the devices in a more expressive manner.

Generated concepts for functional solutions were scored using a Kesselring matrix. The Kesselring matrix is a scoring matrix, acting as a general tool to be using in a decision making process. (Ulich & Eppinger, 2008) There are several different implementation schemes for this matrix however. The specific implementation used ranked concepts in an absolute scale using cardinal numbers, comparing all criteria at once to select a final concept. (Derelöv, 2008) This is aligns with the concept scoring method initially developed by Pahl and Beitz. (Pahl & Beitz, 1996) The Scoring categories were directly translated from design requirements to ensure objectivity in the scoring process, leading to a product which fulfills user needs. Category weights were taken from the design requirements, as well. When possible, concept scores were aggregate results of user polling. The score for enclosure attractiveness, for instance, will be generated by showing users images of enclosure concepts and asking their opinions. This is a known tool to both ensure accuracy of scores and to come up with numerical scores for subjective characteristics. (Ulich & Eppinger, 2008) The Kesselring matrix was a direct translation of the results of the user needs study, and as such it was used as a strict tool and sole tool for the decision making process; the highest scoring solution would be selected for the final design.

Prototyping and Testing

The fourth phase of the investigation was the prototyping and testing phase. The purpose of this phase was to gain knowledge about the design, identify areas where the design could be improved and to present the design to key users. Working with key users confirmed the design, helped identify potential areas of improvement and further built relationships with potential buyers. This phase also helped to reveal any logistical issues that could potentially arise related to suppliers and manufacturing. The process of prototyping and testing is also known to generate insight and information about the connection between design parameters and functional requirements, aiding with the functional mapping of subjective product qualities. (Clark & Wheelwright, 1992)

A prototype was constructed according to the result of the detailed design. The prototype was be tested by 5 key users as identified in the user needs study. For this testing, the prototype was brought to these users to allow them to test using their own equipment in testing. Observation was performed in order to collect information about any latent problems or needs and a long format interview was held about the prototype. User feedback was incorporated into a design iteration, which was incorporated into a final design. A final prototype was constructed based on this final design to serve as a final milestone, a product demonstration to present to customers and key users, and a manufacturing test run of the final product.

Exploration Plan and Intellectual Property

The final phase of the investigation was the formation of an extrapolation plan. The extrapolation plan comprised plans for commercialization including pricing, marketing and distribution. The extrapolation plan also included any further improvements to be made that were beyond the scope of this investigation. An intellectual property search was also performed on the product, exploring potential patent eligible subject matter and potential patent infringement issues. Based on the results of this search and the results of the market analysis study an intellectual property strategy was formed.

5 Benchmarking and Market Analysis

5.1 Benchmarking

The current market can easily be divided into two segments: solid state based devices and vacuum tube based devices. Many vacuum tube devices also implement solid state devices in an effort to remedy the deficiencies of vacuum tubes, but are generally marketed as vacuum tube based devices. Thus these hybrid devices have been included with vacuum tube devices for the purpose of this study.

Solid State Based Devices

The market for solid state based devices is very large and very static. The largest few producers hold an extremely large market share and the top selling products remain unchanged year after year. Although there are some new entrants into this market, it is very rare for any of them to obtain a large market share. Due to the high concentration ratio, the market is also very well behaved; most products have similar prices and features, and much of the product differentiation is accomplished by branding and marketing. Due to lack of intellectual property protection, many companies offer exact functional copies of top selling products, yet are unable to capture a large market share. This reinforces the inertia of the market and the brand strength possessed by top selling companies. A visual overview of the top selling solid state based devices can be found in Figure 11.

Vacuum Tube Based Devices

The market for vacuum tube based devices has a much lower concentration ratio that that of solid state devices. As such, the market is much less well behaved and significantly more dynamic. There are many offerings which have more varied prices and features than their solid state based counterparts. In general, prices of vacuum tube based devices are higher than those of solid state based devices. Products are generally larger and heavier as well. As a whole, the market for vacuum tube based devices is significantly smaller than that of solid state based devices. The distribution channels are also different; vacuum tube based devices are often sold directly electronically or through mail-order, while solid state based devices are more often sold in-store by retailers. Although the vacuum tube based device market has a fairly low concentration ratio, there are still a few products which have managed to command a sizeable market share. A visual overview of the top selling vacuum tube based devices can be found in Figure 12.

Solid State Based Devices

Ibanez TS9 Tube Screamer

Price: 100 USD
Introduction Year: 1982
Dimensions: 4.9" x 3" x 2"
Market Ranking: 1

Boss SD-1 Super Over Drive

Price: 45 USD
Introduction Year: 1981
Dimensions: 5.1" x 2.8" x 2.4"
Market Ranking: 2

Electro-Harmonix Big Muff Pi

Price: 80 USD
Introduction Year: 1960
Dimensions: 7" x 5.5" x 3"
Market Ranking: 3

Figure 11

Vacuum Tube Based Devices

Electro-Harmonix Hot Tubes

Price: 189 USD
Vacuum Tubes: 12AX7WB(2)
Operating Voltage: 117/132V
Dimensions: 8" x 5" x 3.25"
Features: Two Vacuum Tubes

Seymour Duncan Twin Tube

Price: 220 USD
Vacuum Tubes: 6021
Operating Voltage: 240V
Dimensions: 7.5" x 6.6" x 2"
Features: Two Channels

Behringer VT999

Price: 74 USD
Vacuum Tubes: 12AX7
Operating Voltage: 9
Dimensions: 7.8" x 6.8" x 2.8"
Features: 3 Band Equalizer

Figure 12a

Vacuum Tube Based Devices

Ibanez TK999HT Tube King

Price: 125 USD
Vacuum Tubes: 12AX7
Operating Voltage: 100V
Dimensions: 6.2" x4.3" x 2.8"
Features: Solid State Hybrid

Matchless Hot Box

Price: 500 USD
Vacuum Tubes: 12AX7 (2)
Operating Voltage: 250V
Dimensions: 6.2" x 4.3" x 2.8"
Features: Two Channels

Radial Tonebone

Price: 200 USD
Vacuum Tubes: 12AX7
Operating Voltage: 15V
Dimensions: 7" x 4.25" x 2"
Features: Complex Tone Control

Figure 12b

Vacuum Tube Based Devices

Vox Cooltron

Price: 149 USD
Vacuum Tubes: 12AX7
Operating Voltage: 3V
Dimensions: 15" x 7" x 4"
Features: Long Battery Life

Blackstar HT-Drive

Price: 250 USD
Vacuum Tubes: ECC83
Operating Voltage: 300V
Dimensions: 6" x 4.7" x 3.2"
Features: Direct Out

BK Butler Tube Driver

Price: 300 USD
Vacuum Tubes: 12AX7
Operating Voltage: 9V
Dimensions: 6" x 3.6" x 1.8"
Features: Solid State Hybrid

Figure 12c

5.2 PEST

A PEST analysis is an analysis of macro-environmental factors of a given market, namely political, economic, social and technological factors. It is generally used in the environmental scanning component of strategic management. For these reasons, a PEST analysis was deemed an important tool including these macro-environmental factors in the formation of a product strategy.

Political

The market for products has been largely unaffected by political trends. Although certain counties' government programs to promote the arts and tax refunds to promote recreational spending have no doubt had some effect on purchasing behavior, these effects largely pale in comparison to larger market forces.

Economic

Over the last ten years, sales of electric guitar amplifiers have increased slightly, but remained fairly steady. This increase in sales combined with a decrease in price has led to a fairly constant industry value. The global economy has seen great instability in the last ten years, and the stability of the guitar amplifier market may imply that the market is stable regardless of global economy. It may also simply imply that the market was actually growing relative to global economy in the face of a global market crash, resulting in a stable market value.

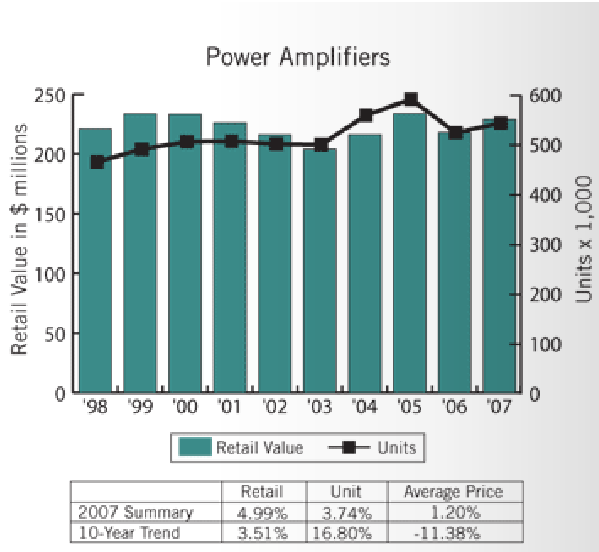
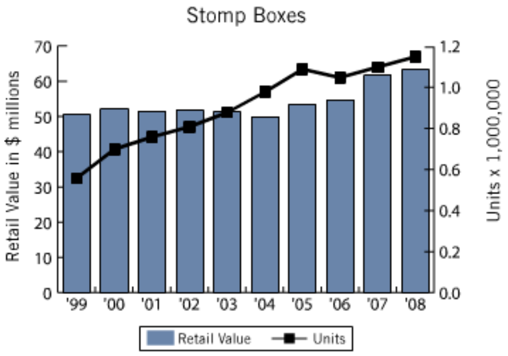


Figure 12: Historical guitar amplifier global sales (NAMM, 2009)

Distortion effects are the most common type of “stomp box” and also employ amplification circuits. Stomp box sales have seen a dramatic rise over the last ten years, as sales have over doubled. Over the same period of time, prices have dropped over 35%. This combination corresponds to a growth of over 20% over the last ten years. This growth took place amidst the aforementioned economic crisis.



	Retail	Unit	Average Price
2008 Summary	2.38%	4.24%	-1.78%
10-Year Trend	25.13%	104.75%	-38.89%

Figure 13: Historical stomp box global sales (NAMM, 2009)

The number of products being purchased and their average price are not the only economic trends to change over the past decade; the way that consumer electronics are purchased has also experienced drastic changes. From 2002 to 2008, e-sales in the US increased at a rate of 21% annually, compared with a 4% annual increase in overall retail sales (U.S. Census Bureau, 2010). This shift to electronic sales has largely reshaped the buying behavior of customers and the marketing and distribution channels for sellers.

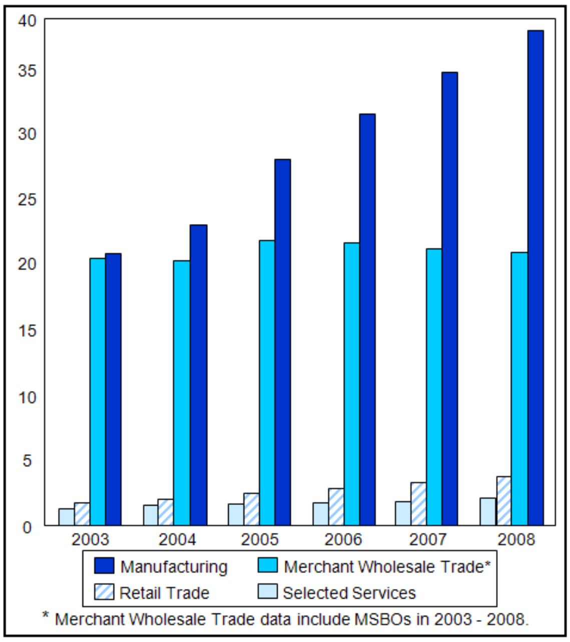


Figure 14: E-Commerce in the US as a percentage of total value (U.S. Census Bureau, 2010)

Social

Electronic products are expanding exponentially as a part of global society. Social networking and a shift towards a technological society have driven the electronics industry to grow substantially. The consumer electronics industry growth has been fairly steady over the last five years, as seen in Figure 7. This expansion of scale has led to lower prices of electronic components (see Economic and Technological).

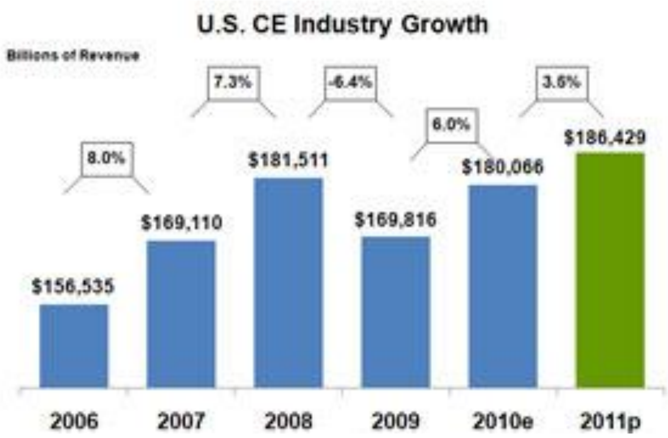


Figure 15: Consumer Electronics industry growth (Consumer Electronics Association, 2011)

The shift of the internet to a social media form has not only driven the electronics industry, but changed the way people obtain and disseminate information. Music, for instance, is now often made available through music sharing website, instead of through record labels. As a result, markets of professional musicians have become somewhat scattered. Ease of distribution has removed some of the barriers to entry, creating a blur between amateur and professional musicians. This, in a sense, has created a new sub-market for amplification circuits.

The way that product information is obtained has also seen great changes recently due to the social format of the internet. For many, gone are the days of going to the local shop to buy musical equipment. A more social internet has paved the way for websites dedicated to equipment reviews, where users often consult each other about potential musical equipment purchases.

Technological

While the electronics industry has seen many recent technological advances, the guitar amplification industry remains technologically stagnant. This is reflected in the fact that the top three selling products on the market were introduced in 1981, 1982 and 1960, respectively. Most of the recent technological advances in guitar amplification have come in the field of digital modeling of analog sounds. Advances in manufacturing technology and growth of the electronics industry have led to lower prices of electrical components. This has consequently led to lower product prices on the market. The average price of a guitar amplifier has fallen over 11% over the last ten years, and the average price of a stomp box has fallen over 35% over the same period.

5.3 Porter's Five Forces

Porter's Five Forces is another tool used to analyze market behavior. This analysis assesses the competitiveness of an industry, looking at both internal and external forces. It also differs from a PEST analysis in that it looks at a micro environment, in contrast to a micro environment. Due to the fundamental differences in the nature of this analysis it was deemed important to be included in the market analysis study in order to gain a complete understanding of market behavior and competitive forces.

Bargaining Power of Suppliers

Most of the electrical components within guitar amplification circuits are standard passive electrical components, used in an extremely wide variety of applications. Largely due to this fact, suppliers have little bargaining power when it comes to these components; several large suppliers offer standard offerings and only second degree price discrimination exists.

Not all components in guitar amplification circuits are standard, however. The vacuum tube, most notably, can be considered a specialty component. Since guitar amplification is the main application of the vacuum-tube, there is naturally a smaller market, fewer manufacturers and consequently fewer suppliers. Largely due to the size of the market, manufacturer's currently produce only a few standard vacuum tubes. In this sense, they have limited the number of offerings to create as large scale an economy as possible. A side effect of this is largely removing the bargaining power of suppliers; since there are a small variety of standard offerings available from a large number of sources, an individual supplier has little bargaining power. Similarly to passive components, only second degree price discrimination exists for production vacuum tubes.

While production vacuum tubes have been standardized, there is a market for out-of-production vacuum tubes. The behavior of this market is largely dictated by the fact that these vacuum tubes are in limited supply and will not be produced in the future. This limited supply theoretically imparts buying power to the supplier; simply having the desired product could command a price premium. In spite of this fact, prices of most out-of-production vacuum tubes rival those of production vacuum tubes, with one notable difference. Certain out-of-production vacuum tubes which have seen widespread usage in the home stereo market currently command very high prices. One possible explanation for this is that the home stereo market is a high margin and very large market. The combination of low supply, high demand and large potential profits has potentially driven up the prices of the vacuum tubes in question. Although the effects would theoretically be smaller in the low margin market of guitar amplification, the parallel effects in the home stereo market could signal the potential bargaining power of suppliers of out-of-production vacuum tubes.

Bargaining Power of Customers

The market for guitar amplification products is extremely large and varied. Due to its sheer size, standard offerings are generally created and sold through retailers and other distributors, leaving the customers with little to no bargaining power. There is, however, a key exception to this situation: the signature model. Buying behavior of many amateur musicians is often dictated by what equipment professional musicians use. Because of this, many companies often work closely with musicians in the development of custom products. These products are then branded using the musician's signature. In this situation, the musician has an incredible amount of bargaining power, often working with the engineers to create the product that they desire.

Competitive Rivalry within an Industry

The industry is largely without much competitive rivalry, although contains a small segment with a large amount of competitive rivalry. For the most part, there is a very high concentration ratio and the largest few firms hold an extremely high market share. These companies are fairly disciplined and do not come out with new offerings very often. This is, again, reflected in the fact that the top three selling products in the market were introduced in 1981, 1982 and 1960, respectively. Product prices and demands are extremely inelastic and the market behavior is largely set in stone. The remainder of the market, however, is extremely fragmented and competitive. This market share is fought over by many companies and the market is dynamic, seeing many new entrants and products. The market on the whole is large enough that this market share, although only representing a small percentage of the entire market, is fairly large in its own right.

Threat of New Entrants

The ability of new entrants to enter the market is extremely good. With large amounts of publicly available information (including products which are very easily reverse engineered,) little intellectual property protection and low development costs, there are no barriers to entry. This is reflected by the sheer number of new companies on the market. That being said, the largest companies in the industry continue to thrive in spite of these new entrants. While smaller producers are beginning to take a larger share of the market, the share they hold is still small, and new entrants can only be seen as a threat to small market share holders.

Threat of Substitute Products

The combination of fast development cycles, low development costs, simple reverse engineering and little intellectual property protection mean that substitute products are a real threat. The mere fact that sound quality is subjective, however, means that what can be considered an acceptable substitute is also subjective. Many products developed half a century ago are the most sought after on the market despite being heavy and unreliable. This is a very small portion of the market, however. In general, new products are constantly entering the market. This means that the threat of substitute products is real and unwavering. Many products, however, have found a way to succeed over very long periods of time in spite of a plethora of potential substitute products entering the market.

5.4 Market Analysis Conclusions

The industry for guitar products employing amplification products is very large. The industry is dominated by a few key players, representing a large portion of the market. This implies that the market is very well behaved. The benchmarking study confirms this fact; the top selling products all are in the same general price range, offering the same general features and maintaining clear, independent brands. The prices of these products have been very stable over recent years, as well. Over the last ten years, the market has seen extreme sales growth in the area of stomp boxes and moderate sales growth in the area of amplifiers. This growth, when combined with the sheer size of the industry and the ease of entry, has enticed a plethora of new entrants to try their luck on the market, introducing many new products.

In spite of the success of many of these products, the big players remain big. This may largely be due to the homogeneity of offerings (partially due to stagnant technology,) brand familiarity and low bargaining power of customers. These may all offer opportunities on the market in the form of product differentiation and customization. The success of larger companies may also be due to larger lower prices stemming from scale effects. This is reinforced by the fact that extreme drops in product prices over the last ten years have led to increased sales. This correlation may indicate price sensitivity on the market. This further implies an opportunity to introduce a lower cost product to the market. In sum, the initial market analysis implies an opportunity to introduce a product so long as it is unique and low cost. The high number of new products on the market and the high concentration ratio would normally imply that there is no opportunity, but the sheer size and growth rate of the market imply that there is in fact some room on the market.

The tools used for the market analysis and benchmarking appeared to be appropriate and the information collected is believed to be comprehensive. As such, it is believed that the use of further tools, such as SWOT, would only produce either redundant or irrelevant information. Although no tradeshows were attended as a source of information, the use of tradeshow literature is believed to remedy this deficiency in information. Discussions with users who attend tradeshows revealed that while tradeshows offer good information about individual products, larger trends are better represented in tradeshow literature.

6 User Needs

6.1 Matrix Analysis

A matrix analysis is a visual representation of user statements, in which representative statements from identified market segments are presented for key topics identified in the user needs study. This matrix analysis was performed (see table 1) in order to both reduce the data collected and to create a clear visual representation of the key issues that can easily present information based on segment of interest and key issue. An in depth discussion of each key issue follows to further explain the contents of the matrix analysis as well as provide more extensive insight to the results of the user needs study.

Table 1: User needs matrix analysis

	Amateur	Professional	Retailers
Sound Quality	Less particular	Good linear range	Versatility and niches
Purchasing Information	Online reviews and professionals	Online reviews	Buying centers
Price	Very Important	Less Important	Undercutting not enough
Branding	Very Important	Less Important	Important for purchases
Enclosure	Appearance	Robustness	Eye-catching
Usage	Home	Studio and stage	Mostly home users
Interfaces	Have time to play with controls	Simplicity	Controls can be intimidating

6.2 Key Issues

Sound Quality

As the main role of the distortion sound effect is to alter the sound, it is intuitive that sound quality is the most important property of a distortion sound effect. This is in line with the opinions of professional users. Professional users all cited sound quality as the most important factor in purchasing decisions. When discussing desired sound quality, many differing opinions were present within the sub-group of professional users, but there were some commonalities between most professional users. Most professional users spoke of the need of versatility. These users often stated that while it is a good thing if a distortion sound effect specializes in a specific sound, it must sound at least fairly good over a fairly wide range of gains, volumes and frequencies. Many professional users complained about high gain pedals that offered very dry low gain sounds and little touch sensitivity, and low gain pedals which sounded unpleasant with the gain setting maximized. Some professional users were looking for very specific sounds from their distortion sound effects. Users of low distortion amplifiers often were interested in purchasing high distortion sound effects, while users of high distortion amplifiers were often looking for low distortion sound effects. The few professional users of solid-state amplifiers were generally interested in low gain distortion sound effects.

Amateur users, although interested in sound quality, were less interested than professional users. For some amateur users, sound quality was not primary factor in purchasing decisions, falling behind cost and brand reputation. In general, amateur users were more interested in a distortion sound effect which sounds good over their entire range of sounds with minimal effort. This range did not need to be as wide as that of professional users, but it was more important to amateur users that the effect is linear over a wider range. Also in contrast to professional users, amateur users were less interested in a distortion sound effect that specialized in a specific sound. Many amateur users interviewed played through solid state amps and simply were interested in using a distortion sound effect as a pre-amplifier to add a vacuum tube's warm sound to the signal.

Retailers echoed the opinion's put forth by both amateur and professional users. The most commonly spoken words regarding sound quality in retailer interviews were versatility and specialization. Almost all retailers stated that a distortion sound effect must fulfill a specific niche very well without sacrificing range in frequency, gain and touch sensitivity. Retailers pointed to ElectroHarmonix as a company that has managed to do this successfully, specifically calling attention to its Big Muff distortion sound effect product line. This product line began with a base product, the Big Muff Pi, which was introduced in 1960. Since then, several variants have been introduced including a low-cost version manufactured in Russia, and several variants catering to niche market. These variants include a high-gain version catered to the heavy metal market. Retailers pointed to these variants as both a way to build brand strength as well as hit specific user needs. The high-gain version, for instance, was based on a market need for a high-gain distortion sound effect. Retailers, in fact, indicated that there is still a market need in the area of high-gain distortion sound effects, stating that there is currently no vacuum tube based product in this market.

Purchasing Information

A variety of purchasing factors were mentioned by all users, but almost all amateur and professional end users explicitly stated that they make their buying decisions based on online reviews. User review websites including Harmony Central and Ultimate Guitar Review were cited by many end users. Other end users cited retailers' websites as sources of product reviews. Interviews with retailers reflected user statements, as retailers stated that most customers come into the store having read several online reviews and often don't even test the product before purchasing it. Although reviews also available in various print formats, including industry publications, these were never cited as sources of information from end users.

Many amateur users stated that they often use professional users as a source of product information. Amateur users often try to emulate the tone of professional users and can accomplish this by purchasing the same equipment. Furthermore, many amateur users see professional use as a product endorsement. The most extreme case of this is when a professional user actually endorses a product. Manufacturers often product artist signature models, which are customized to a professional user's needs and then endorsed by said user. These products often are sold as premium products and are often sell high volumes for high profit margins. Amateur users also frequently cited user reviews from internet sources, such as HarmonyCentral.com, as very important sources of purchasing information. Internet reviews were the most commonly cited source of purchasing information of purchasing information. These centralized sources of information are in line with theory suggesting that time constraint constraints largely dictated product information searches. (Hauser, Urban, & Weinberg, 1993)

While amateur users look to professional users for purchasing information, professional users have access to more equipment and tend to get their information first hand. By using the equipment of their peers, using venues' house equipment and simply purchasing more equipment, professional users have much greater first hand access to product information. Some professional users cited internet reviews as a source of purchasing information, despite having greater first hand access to products.

Retails chains stated that individual stores do not make buying decisions, and that the retailer usually has one buying center for all stores. Although information was scarcely available regarding how these buying centers make purchasing decisions, it was indicated that potential decision making factors were product publicity in trade shows and industry publications.

Price

Amateur users cited price as a major factor in making buying decisions. Many amateur users stated that price was their sole reason for selecting a solid-state based product over a vacuum tube based product, and a few even cited price as the sole factor in their buying decisions.

In contrast, the professional user market was somewhat fragmented. Some professional users stated that buying an expensive product that performs the function they need is cheaper than buying several low cost, incomplete products. Furthermore, this segment of professional users often saw the product as an investment instead of a leisure product. The remaining professional users were extremely price sensitive, similarly to the amateur user market. These users stated that price was the most important factor in buying decisions and expressed interest in a low cost product.

Retailers deal with both amateur and professional users and their statements on price sensitivity of the market reflected this. They stated that they get a fairly even split between customers who are both price sensitive and not price sensitive. When asked if on the whole price is a major issue, retailers generally stated that they do not believe it is. Although retailers stated that directly undercutting a product while offering the same features might be a viable business model, they suggested other forms of product differentiation might be more effective, and that price cutting alone is not enough to achieve high sales volumes. Retail stores generally charge higher prices than online bulk retailers, which may partially explain the difference between the price sensitivity of users on the whole and the opinions held by salesmen in retail stores.

Features

Amateur users, professional users, and retailers all indicated that features, similarly to sound quality, offer a diverse set of needs. Amateur users generally required few features and were not likely to buy a product for the features it offered. If they did buy a product for a feature, it was generally for one specific feature, instead of a broad range of features.

Professional users, on the other hand, were again a segmented market. Some professional users were interested in purchasing a product that was extremely feature-rich. This segment of professional users cited number of features as a key factor in buying decisions. Some of these users stated that this was due to the fact that products had to be used in a variety of settings, including performance, studio and rehearsal, and often with a variety of bands with different needs. The other segment of professional users was interested in a product practically devoid of features. This segment often cited “simplifying their setup” and “ease of use” as reasons for not wanting many features. Some of these users stated that they go as far as to modify products to remove features in order to reduce thermal and transient noise in circuits. These users stated that they would be interested in a product that “did one thing well.”

Retailers seemed to reflect the opinions of professional users as a whole, offering many contradictions. Many retailers advised any new product to “have as many features as possible.” Citing the success of the Blackstar HT pedal series, retailers said that features offer selling that individual customers may be interested in and including more features creates a product that more customers will want to buy. Citing the costs of these features, however, the same retailers warned of the dangers of adding features to a product. While features could attract customers, they make the product more complex and expensive. Retailers cited certain companies, such as Pigtronix, as offering products which are too expensive and complex for many users. To further support this point, retailers cited the success of MXR, a manufacturer who makes low cost effects which are often almost devoid of features.

Branding

Segments unanimously agreed that branding is extremely important in purchasing decisions. This reflects the strong sales of top brands year after year across a wide range of products. Many users owned multiple products from the same company, reflecting brand loyalty. This brand loyalty was much more common in amateur users than professional users. Still, professional users gravitated toward more well-known brands. Speaking to professional users, this was due to widespread availability and greater purchasing information.

Larger retailers generally stock mostly well-known brands. When asked about branding, retailers stated that they stocked these brands since they have business relationships with these companies and they are generally the products that customers are looking for. Since most customers use retailers for purchases and not for gaining purchasing information or testing products, it was wiser for retailers to stock the most commonly purchased products. Similarly to before, large retailers' business relationships involve the purchasing centers and corporate headquarters and the nature of these relationships was not known by individual retailers. These relationships carry a lot of value, as they provide access to many customers. As such, many companies have started premium and low end brands in an effort to leverage their existing relationships in new product lines.

Smaller retailers were much more likely to stock smaller brands' products, often times not even stocking larger brands' products. Smaller retailers stated that this is because their customers are generally more interested in testing, gaining information about and purchasing smaller brands, whereas customers who are interested in larger brands' products tend to buy from larger retailers. In a sense, the smaller retailers were a step closer toward direct internet sales. The lack of branding in the purchasing decisions in the markets of smaller retailers and direct sales make them ideal markets for new brands.

Enclosure

Although all interested parties stated that the actual sound effect is the most important, the enclosure played a key role in purchasing decisions. Amateur users particularly looked to the physical appearance of an enclosure to communicate its brand and sound characteristics. Amateur users generally had less knowledge about the product and thus the aesthetic qualities of the product could communicate more about the product than its actual properties. Amateur user tastes were very spread out and no conclusions were made about preferred designs. In general, amateur users saw design novelty as a way to create product differentiation in a market where many products have similar external appearances.

Professional users also found the enclosure to be important, but for different reasons. Professional users were interested in the functional aspects of the enclosure. Weight and robustness were two important factors for professional users, as they often use products in live performance and can't afford the product to move or break during usage. Size was also a large concern for professional users who often have various sound effects that they must both transport and operate in a limited amount of space. Professional users cared less about the aesthetic factors of the product. In general, professional users were interested in a professional looking product that was not particularly flashy looking.

Retailers had much less to say about enclosures, with opinions that seemed to reflect amateur users. Retailers stated the enclosure should be eye catching, novel and uncluttered. Retailers also tied enclosures into branding, mentioning brand continuity between enclosure designs.

One special consideration in vacuum tube based effects is the enclosure of the vacuum tube itself. The vacuum tube is the most fragile and often the largest component in these products. There are generally two strategies employed in enclosing the vacuum tube: mounting the vacuum tube within the main enclosure and mounting it on the surface of the enclosure while providing it its own enclosure. Amateur users stated that they prefer to have the vacuum tube mounted on the outside due to aesthetic reasons. Professional users stated that they also prefer to have the vacuum tube mounted on the outside so that it is simpler to change vacuum tubes, but stated that it is extremely important that it has a robust protection system.

Usage and Controls

Products currently on the market generally have similar interfaces. These interfaces usually include adjustable tone controls, volume controls, controls for amount of distortion and a control to activate or deactivate the sound effect. Some products include more complex interfaces, including multiple-band tone controls, multiple discrete levels of distortion and other more complex tonal effects. In observing usage, most users very rarely use any of these controls. The most commonly used control is the distortion control, with the tone control being almost universally ignored. Some users used the volume control, while others simply used the volume control built into the guitar. Professional and amateur users alike generally interacted the most with the device by activating and deactivating it. This is universally accomplished using a foot actuated push button switch, allowing the user to activate it without playing interruption.

Amateur users generally used products at home, while professional users tended to use products in a studio and performance setting. These different use settings dictated different product interactions and demands. Amateur users generally had more time and a better setting to adjust interfaces. Amateur users also did not have to transport their products and were very gentle with them in operation. Professional use differed in that it required simple interfaces which can be operated in low light. Professional use also involved product transportation and stage use, both creating more abuse.

Professional users generally used their distortion sound effects as a small part of a larger, more complex setup often involving high quality products than the simple setups of amateur users. Due to this, professional users often used the distortion sound effect to add a specific sound. Amateur users, on the other hand, used the distortion sound effect similarly to a standalone preamplifier, simply to improve the sound quality of their current preamplifier.

6.3 Design Requirements

The information received from the user interview process was converted to the list of design requirements seen in Table 2. These requirements have been assigned a weight of 1-10 based on importance and have been given metrics to measure their value in a relevant and quantitative manner. Weights were assigned based on the results of the user needs study and market analysis. Requirements have been grouped into three categories: Sound, Usability and Market. A brief explanation of each requirement, including its metric and weight, has been included in order to further explain its significance.

Table 2: Design requirements

Requirement	Weight	Metric
Sound		
Produce Pleasant Distortion	10	Published Information
Provide a Range of Linear Operation	4	Grid Line Spacing Evenness and Voltage Headroom
Provide Touch Sensitivity	10	Voltage Headroom, Linearity, Compression
Produce High Gain	5	u
Enclosure and Interface		
Look Attractive	7	Aesthetic Appraisal
Be Robust	5	Apparent Robustness
Be Novel	3	# of Similar Solutions, Apparent Novelty
Be Small	3	mm3
Market		
Cost	9	USD
Contain Available Parts	7	# in Stock
Be Easy to Use	6	Number of Interfaces

Sound Requirements

The most important user requirement for a distortion sound effect was naturally the ability to produce pleasant sounding distortion (this was confirmed by user interviews.) As such, this requirement was assigned the maximum weight of 10. There are several ways to measure distortion quality. The most common measurement is harmonic content, which is often broken down into even harmonic content and odd harmonic content. While harmonic content is viewed as feasible way of measuring distortion sound quality, it is always obtained by measurements after a circuit is built and cannot be simulated accurately. As such, it is a tool used to confirm a design rather than the predict performance. The ultimate goal, however, is not harmonic content, but rather pleasant sounding distortion. While harmonic content may indicate pleasant sounding distortion, user confirmation is guaranteed method of confirming distortion sound quality. As such, user confirmation would be the most suitable a metric for distortion sound quality. The purpose of the design requirements, however, is to serve as a tool for assessing design concepts. Use confirmation would not be an option to assess concepts which had not yet been realized. As such, published information about existing circuit types would have to be relied upon as a metric for distortion sound quality.

Two strongly related terms were repeatedly mentioned by all users when discussing sound quality: touch sensitivity and headroom. These were key aspects of sound quality which needed to be included in the user requirements. It became clear in the user needs study, however, that these two were requirements were somehow linked. Users defined headroom as a range where the circuit behaves linearly and touch sensitivity as the ability to control the linear behavior of the circuit by varying signal strength. Having the appropriate amount of headroom would therefore inherently provide a certain touch sensitivity, as a user could use vary signal strength so that it is larger than the voltage headroom. Touch sensitivity, however, had a different scope than voltage headroom. The surrounding circuit, for instance, could potentially compress a signal, causing the device to lose all touch sensitivity. As such, two requirements were created: Providing a Range of Linear Operation and Providing Touch Sensitivity.

Touch sensitivity was identified as a very important user requirement, and was also assigned the maximum weighting of 10. Touch sensitivity, as previously stated, is the ability for a user to control non-linearity using input strength. This is a complicated property to measure, which encompasses several other properties, namely headroom, linearity and compression. As such, these three were selected as the relevant metrics for touch sensitivity. Headroom, or the linear operating range, was identified as less important property, some which some users had no interest in. As such, it was assigned a lower weight of 4. Headroom could be measure both in terms of its size (voltage headroom) and quality (linearity based on grid line spacing evenness.) These two were selected as metrics for the requirement of providing a linear operating range.

Gain, although not considered as important as touch sensitivity or distortion quality, was mentioned in almost every single user interview. Some users were interested in high gain devices which not only added non-linearity to the signal, but could drive further amplification stages (such as a stand-alone amplifier) to add their own non-linearity. While some users were not interested in high gain devices, they indicated that a high gain device would not be undesirable so long as a user interface was included to vary output strength. In general, users were split across the board on the importance of gain and as such it was assigned a weight of 5. The metric for gain was set as the published gain value (μ) of the vacuum tube.

Enclosure and Interface Requirements

The usability requirements were fairly straightforward, consisting of requirements which were directly stated by users. Size, for instance was explicitly stated by several users and thus was easy to identify. Speaking to users, it became apparent that current products on the market almost never failed and were completely reliable. This was confirmed by retailers claiming that parts were almost never brought in for repair or return. Even still, users claimed that perceived robustness was in a fact a part of the buying decision. As such, appearing robust was included as a design requirement. Due to the fact that this robustness was actually perceived robustness, user confirmation was included as the corresponding metric. The final usability requirement identified was ease of use. Many users stated that they wanted very few user interfaces, some stating that they simply wanted an on/off switch on a distortion sound effect. Users generally discussed the ease of use of a product in terms of number of switches, knobs and buttons on the product. As such, number of interfaces was determined to be the suitable metric.

Market Requirements

Market requirements were requirements that were not only identified by the user needs study, but also identified using information from the market analysis. These included cost, novelty and availability. Novelty was a key factor in product differentiation. The importance of this novelty was not actual product novelty, but perceived novelty, as a product that was perceived to be novel by a potential buyer would have differentiated itself in the eyes of said buyer. As such, user confirmation was identified as the suitable metric. Cost was also another key method of product differentiation. Cost was identified as a key requirement from both the user needs study and market analysis. Cost was explicitly stated by users as a key requirement and provided a straightforward and easily measurable metric.

Availability was identified as a key metric for several reasons. Users, particularly professional users, stated that they need to be able to obtain replacement parts themselves at any time from almost any supplier. In terms of business strategy, using low availability and out of production parts would provide low product sustainability. Furthermore, using low availability parts increases the bargaining power of suppliers.

6.7 User Needs Conclusions

The user needs study was effective in that sense that users of all identified segments were well represented and communicated their demands, wishes and purchasing behaviors. The segmentation proved to be effective, as users within specific segments provided similar information on given issues. Consistent terminology was used to describe properties of sound and sound quality, although some variations were present. Relationships were created with both amateur and professional users which would continue throughout the project, including the testing phase. Enough information was gathered from enough users to be able to make conclusions regarding user needs which could be used moving forward as a basis for design requirements. As more interviews were conducted, less new information was acquired. In later interviews, much of the information had already been acquired from earlier interviews. This reflects the effectiveness of the long interview format used, but also reflects that the interview process could have been shortened.

The objectiveness and qualitative properties associated with human sound perception embodied themselves in the creation of the design requirements. Many individual requirements, such as distortion quality, were completely subject to user perception. Even though it may be possible to measure harmonic content to potentially indicate distortion quality, it was deemed significantly more effective to use user confirmation as an indication of distortion quality. This, simply put, is because the goal of the product is to please the user, not to achieve a certain harmonic content. The fact that many design requirements had user confirmation as a metric would shape the rest of the project, especially the testing phase. Any requirement with a user confirmation metric would be subject to many assumptions in the initial design phase, and would require extensive testing and possible design and testing iterations. While this was initially expected in the project planning phase, the results of the user needs study confirmed this.

7 Design

7.1 Concepts: Vacuum Tubes

5904: Subminiature Triode

The first subminiature vacuum tubes were developed by Raytheon for use in hearing aids. Government tests of these devices showed very high durability, and they were shortly incorporated as proximity fuses in guided missiles. Due to these applications, many models are intended for dry cell battery use, and thus low voltage operation. (The Raytheon Company, 1961) These applications also explain the small size and high reliability and durability of the subminiature tube. The small size of the subminiature tube means that they are incompatible with standard vacuum tube sockets and protection frames. All subminiature vacuums tubes are out of production.

Figure 16: A subminiature vacuum tube

The 5904 vacuum tube is a subminiature triode. It has a single, high gain stage, allowing for a simple, high gain circuit, but severely limiting circuit design options. It is rated for 28V operation of both the filament and plate. This voltage is obtainable from off-the-shelf AC adaptors, although costing more and less available than 12V AC adaptors.

Strengths: Small size, durability, some designed for low voltage operation, same filament and plate voltages

Weaknesses: Out of production, limited availability, unique form factor, requires slightly higher filament voltage, design for slightly higher plate voltage

7895: Nuvistor

Nuvistors are the smallest form of vacuum tube, announced by RCA in 1959 (RCA, 1959) Nuvistors are generally triodes, housed in a small metal casing. The type of electrode structure employed in the Nuvistor valves is based on a concentric arrangement of cylindrical electrodes. These electrodes are supported by three pins which project through a ceramic base plate. The valve is finally encased in a metal shell which needs to be adequately bonded to the chassis of the amplifier for optimum stability. Although pins are available for grounding the metal shell it is rather important that something better in the way of grounding is produced by means of the grounding lugs on the, metal shell. (The Nuvistor, 1962) Nuvistors are generally considered to have the best noise performance of any vacuum tube, only recently being surpassed by transistors.

Figure 17: A vacuum tube nuvistor

The 7895 nuvistor is a triode vacuum tube. It is similar to the 5904 in that it has a single, high gain stage, offering the same advantages and disadvantages. The 7895, like all nuvistors, is rated for a high plate voltage and a low filament voltage. The nuvistor's metal shell provides unmatched durability and its unique structure allows it to be made in the smallest package of any vacuum tube. It also does not require any external protection frame. The nuvistor looks drastically different from any other vacuum tube on the market, showing clearly novelty to the user. The 7895, like all nuvistors, is long out of production. Nuvistors are generally the least available type of vacuum tube.

Strengths: Small size, excellent noise performance, high gain, long life

Weaknesses: Out of production, very low availability, unique form factor, designed for high voltage

12AL8: Space Charge

The space-charge tube was developed during the late 50's to early 60's mainly as a transitional device for car radios to replace the traditional high voltage vacuum tubes. Transistors were coming on the scene, but they were expensive and the upper operating frequency was limited. These tubes operated with 12 volts on both the filaments and plates which eliminated the vibrators and other devices for providing the high voltage. Their operating frequency was well above the broadcast band. One of the drawbacks was the high current demanded by the filaments. However, since the power source was a car battery, it really wasn't a problem. With only 12 volts on the plates, at low current, it was impossible to obtain enough audio power output to drive a car speaker system. Due to this fact, space charge tubes were only suitable for pre-amplification purposes. (Dunemann, 2011)

Figure 18: A 12AL8 vacuum tube

The 12AL8 is a combined medium-mu triode and space charge grid tetrode. The triode plate, the tetrode plate and the filament are all designed to run off of 12.6V, requiring only one supply voltage that is easily obtainable. Since the intended operating voltage of the current application corresponds with the rated operating voltage, operation is taking place in a very linear region. As non-linearity is the main problem associated with low voltage operation, this could theoretically offer an off the shelf solution to the problems with low voltage operation. The low availability, however, could present a problem which cannot be solved. Several vacuum tube manufacturers were contacted as part of this investigation, all stating that they are not equipped for any further production runs of any space charge vacuum tubes. Although not currently in production, the 12AL8 is one of the more widely available space charge vacuum tubes. It is also one of the lower cost space charge vacuum tubes available. No commercial products appear to use the 12AL8 or any other space charge vacuum tubes. Although the unique choice of vacuum tube and lack of drop-in replacements may signal novelty, this novelty may be lost on the average user.

Strengths: Designed for low voltage operation, low cost, no linearization required

Weaknesses: Out of production, limited availability

12AX7: Standard Dual Triode

The 12AX7 is a miniature high-mu twin triode. It is one of the few small signal amplification tubes still in production. Due to this fact, it is the most widely used pre-amplification tube on the market. It is rated for a 12.6V heater supply and has a high amplification factor of 100 per stage. Both of these characteristics are desirable for as a Class A amplifier. The two triodes of the 12AX7 are rated for 100V and 250V respectively. (Sylvania Electronics Products Inc, 1955) These high ratings unfortunately correspond to completely non-linear operation at low plate voltages. The tight operating range combined with the small voltage swings of low plate voltages also leads to a loss of touch sensitivity

Figure 19: A 12AX7 vacuum tube

Strengths: High gain, high availability, low cost, proven sound

Weaknesses: Requires linearization, low novelty

01A: Directly Heated Triode

While the earlier description of the operation of the vacuum tube triode holds true for most vacuum tubes, there are certain variations on the general concept. One such variation is the directly heated triode. In a directly heated triode, the cathode and filament are integrated, and the triode receives an AC input signal as well as filament power, which can be delivered in the form of AC or DC power. An AC filament power source will have some hum and intermodulation distortion, while a DC filament power source leads to uneven heating and variable amplification across the area of the vacuum tube, leading to non-linearity. (TENTlabs, 2003)

It has been proven, however, that powering the filament with a DC voltage well below its rated voltage not only avoids adding non-linearity, but improves the linear operation of the vacuum tube. (Bench, 2011) This improvement to linear performance can theoretically be used to combat the non-linearity associated with low plate voltages. Furthermore, employing feedback systems into the filament supply can further be used to improve linear behavior by lowering filament voltage as incoming signal strength increases. One potential method of doing this would be to run the filament in series with the plate. This would act as a variable voltage divider, in which as plate resistance increases (as it does with input signal,) filament voltage would decrease.

Figure 20: A 01A vacuum tube

Although most directly heated triodes are long out of production, some models are still produced, often used in the home stereo industry. In general these vacuum tubes are expensive, and have unusual form factors. These form factors can be seen as aesthetically pleasing and demonstrate device novelty, but are not compatible with many standard enclosures and parts. Directly heated triodes are universally intended for high plate voltage operation. As such, any design would require a starved plate and a starved filament. Standard filament DC supply voltages are 5.0 V, while the cited starved filament experiments were performed at 3.2V. This implies that either separate voltage must be provided or the plate must be run at a significantly lower voltage than intended. The OA1 is a single low-mu triode, one of the few production models. It was used as the basis for the cited experiments which demonstrate the linearity of starved filament operation of directly heated triodes.

Strengths: Doesn't require linearization, novel solution, low voltage

Weaknesses: High cost, requires two voltages, low availability

6SN7GT: Standard Dual Triode

The 6SN7GT is another small signal amplification tube that is still under production. As such, it has many of the same benefits of the 12AX7, including price and availability (although not being as low priced and widely available.) It is a medium-mu twin triode, providing less gain than the 12AX7. Its main differences, however, are in its form factor and operating voltage. The 6SN7GT is an octal vacuum tube, housed in a standard GT size octal glass envelope. GT size glass envelopes are generally used for

Figure 21: A 6SN7GT vacuum tube

power tubes and are larger than small signal nonal tubes. The 6SN7GT has a heater voltage rating of 6V, further lower plate voltage should we operate the plate and heater using the same voltage source. The main advantage of the 6SN7GT is that it operates more linearly over a wider range than the 12AX7. This is confirmed by a mere visual inspection of grid lines spacing on the vacuum tube data sheets. Furthermore, the 6SN7GT offers significantly more headroom; at an anode voltage of 100V the cutoff grid voltage for the 6SN7GT is -6V, compared to -1.6V for the 12AX7.

Strengths: High availability, low cost, decent linearity and headroom

Weaknesses: Large form factor, not available everywhere, low heater voltage

7.2 Vacuum Tube Selection

Each vacuum tube was individually rated on a scale of 1-10 on how well if fulfilled the design requirements. Not every design requirement was relevant to vacuum tube. Ease of use, for instance, was not included in the vacuum tube scoring matrix. When possible, objective measurements were used. Price, for instance, was scaled by dividing the lowest priced vacuum tube by the vacuum tube to be scored, multiplying by ten and rounding the result to the nearest whole number. Gain scores were calculated in an identical fashion.

While price and gain provided a simple scoring mechanism, the scale of certain requirements, such as headroom, provided difficulties in scoring. The 12AL8 vacuum tube provides 3V of headroom at an anode voltage of 12V, which is six times greater than the next closest vacuum tube (the 6SN7GT.) Instead of merely providing scores of 1 to every other model, in instances where one or two devices performed dramatically better than other models, these models were assigned a score of 10. The next highest model was then assigned a score of 8 and further scores were then scaled to that model.

Cost was calculating by estimating cost of implementation, as opposed to vacuum tube cost. This required certain assumptions about costs of applying multiple voltages and protecting parts with odd form factors. A perfunctory search of part costs was performed in order to create informed pricing scores.

Certain values, such as novelty, durability and availability were scored somewhat subjectively, although in an informed fashion. Novelty was determined by checking how many solutions on the market employed the same type of technology, similar looking technology and identical model. Durability was scored based on typical applications. The 5904, for instance, is intended for missiles and military operation, and thus scored highly. Availability was obtained by checking suppliers, including specialty internet suppliers and retailers, for availability information.

The greatest difficulties in scoring came in terms of the properties related to sound quality. Touch sensitivity is a function of headroom, the surrounding circuit and the operating conditions. Unfortunately, the surrounding circuit and operating conditions had not been selected to that point in the process. Here we can see the inherently coupled nature of the problem. As such, a decision was to be made without knowledge of the system implementing the decision. The only then known factor affecting touch sensitivity was the linear operating range, which was itself another design requirement. As such, only linear operating range was included in the scoring matrix, not touch sensitivity. The criticality of the component is felt to have justified its selection prior to the surrounding system

A method needed to be created for creating linear range scores. One potential method was to simple score each vacuum tube by dividing its rated operating voltage by its intended operating voltage; essentially simply calculating the headroom. This alone, however, would not account for any improvements to headroom that could be made by using surrounding circuitry. As such, vacuum tubes were assigned touch sensitivity scores by dividing their rated operating voltages by their intended operating voltages and adding 1 point to account for potential circuit improvements.

Finally, the sound quality of the distortion, including harmonic content, is generally a function of the circuit surrounding the vacuum tube, not the vacuum tube. This further demonstrates the couple nature of the problem and functional breakdown. As such, distortion quality was not included in the vacuum tube selection process.

Table 3: Vacuum tube model scoring matrix

	Weight	12AL8	12AX7	5904	7895	01A	6SN7GT
Linear Range	4	10	3	10	3	8	4
Cost	9	10	10	7	3	2	3
Availability	7	2	10	2	1	1	8
Novelty	3	10	1	8	10	8	4
Gain	5	4	10	1	9	1	6
Size	3	4	4	9	10	4	4
Robustness	5	5	5	9	10	5	5
Total	360	231	262	218	201	123	178

The results of the Kesselring matrix (table 3) reveal the 12AX7 to be the highest scoring vacuum tube, and thus it was selected to be used as the basis for the circuit design. An inspection of the matrix reveals that this is mainly due to product availability. Availability is extremely important for several reasons, as previously discussed (see Design Requirements.) While many other vacuum tubes, particularly the second highest scoring 12AL8, would provide high potential for linearity, they would not provide for a sustainable business model, or user serviceability, the former being a key internal requirement and the latter being a key user requirement. The large number of suppliers of the 12AX7 also strips suppliers of their bargaining power.

One may be inclined to believe that based on the above, any production model vacuum tube would score highly and that the matrix is somehow skewed toward currently produce models. The low scores of the 6SN7GT demonstrate the fact that the scoring system was not completely skewed toward current production models; two out of production vacuum tubes scored higher than the 6SN7GT. Furthermore, the matrix is a direct translation of design requirements, which were in turn the product of the user needs study. This direct traceability of the scoring system implies that should the matrix be skewed toward production model vacuum tubes, this skewing would be a the product of user needs and thus an accurate translation of what the market demands.

7.3 Concepts: Circuit Type

Dynamic Range Compressors

Compression is the automatic reduction of gain as the signal level increases beyond a preset level called the threshold. It is an automatic version of “gain riding”, where one might manually lower a volume as a signal grows larger to maintain a more constant output level. For signals above the threshold, the increase in output amplitude for a given increase in input amplitude is known as the compression ratio. Below threshold, the ratio is 1:1 while above threshold the ratio may be set anywhere up to ∞:1, which is considered limiting since in that case the output signal does not increase at all as the input signal increases. The time required for the gain to reduce when a signal crosses the threshold is referred to as the attack time and the time it takes to return to the original gain when the signal drops back below the threshold is the release time. Generally, the attack is fast and the release is slow to prevent audible artifacts of the gain change, however too short an attack time reduces the transient onset of a sound and noticeably alters the character of the sound: sometimes this may be desirable, but often it is not. In sum, the effect of compression is to reduce the overall dynamic range of a signal. (Kadis, 2008) The non-linear response of vacuum tubes is embodied at the highest input signals, corresponding to grid voltages approaching zero. By compressing the incoming signal, the output amplitude of these stronger signals can be reduced, theoretically counteracting the non-linearity.

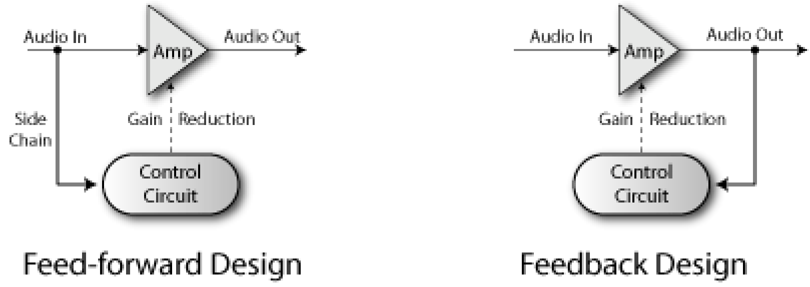


Figure 22: Two general classes of dynamic range compression

Dynamic Range Compressors generally come in two forms, feed-forward and feedback design (see Figure 22), as well as combinations of both. As can be seen, dynamic range compressors require an amplifier within the circuit; this comes at the cost of added cost and complexity. Modern dynamic gain guitar compressors, for the most part, use solid state transistors as amplifiers. Solid state compressors, although effective, may require different voltages than vacuum tube circuitry, require special transistor sockets and may be a turn-off to potential customers.

Strengths: Good linearity, good sound quality, proven solution, not very high gain loss

Weaknesses: Complex, high cost, may turn off "audio purists", some gain loss

Zener Diodes

The zener diode is another device which exhibits a non-linear response to voltage. Much like a standard diode, zener diodes act as a wire in the forward direction, simply letter current pass with minimal resistance. Unlike standard diode, however, resistance in the reverse direction is a non-linear function of voltage. As can be seen in Figure 23, below a certain voltage, no current flow occurs in the reverse direction. After a certain breakdown voltage is reached, the diode allows current to pass in the reverse direction with minimal resistance. While this behavior is also found in standard diodes, it generally occurs at high voltages, is extremely uncontrolled and causes severe damage to the diode. Zener diodes are available at a low breakdown voltages, offer very stable reference voltages and are not damaged by breakdown.

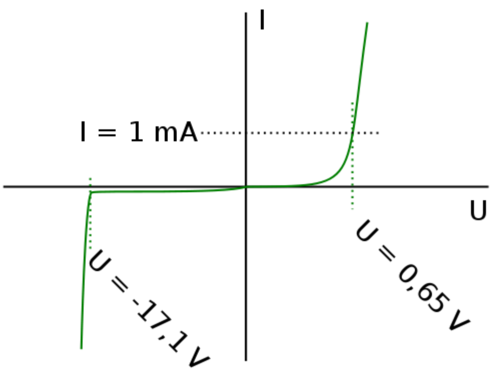


Figure 23: The behavior of a zener diode

The non-linear response of the zener diode can theoretically be used to counter the non-linear response of the vacuum tube. By sizing components appropriately, the zener diode can begin conduction during the non-linear range of the vacuum tube's operation. By putting the zener diode in a path to the cathode, it can be used as a tool to lower the bias of the vacuum tube in an attempt to make the response more linear. Similarly to dynamic range compressors, the breakdown voltage acts as a threshold, before which the zener diode will have no effect. Instead of compressing all signals to this threshold, however, the zener diode can be used to try to correct the non-linearity.

While this offers an advantage over the dynamic range compressor, the zener diode is not without its weaknesses. Any change in bias effects both the sound and touch sensitivity of the device. When the circuit is rebiased, there is a risk of a drop in distortion, volume and touch sensitivity. Capacitors can help smooth out these jumps, at the cost of feedback response time. The zener diode is essentially a binary device, and can only offer a single linear correction to a non-linear problem. Several zener diodes can theoretically be used to model the non-linearity according to Euler's method. This is, however, limited by availability of zener diodes by breakdown voltage. Furthermore, this adds cost and complexity to the device.

Strengths: Low cost, novel solution, lower gain loss

Weaknesses: Potential "drops" in response, unproven solution, adds complexity, linear approximation

Rectified Output Rebiasing

A more direct method of rebiasing the vacuum tube based on non-linearity is to use the actual output signal to lower the bias the vacuum tube by feeding it into the grid. This solves several problems with the zener diode network, including the drops in response and linear approximation associated with having a binary or multiple-binary based system. The output signal cannot simply be fed into the grid of the vacuum tube, as the output signal is an AC signal. In order to make the signal usable, it must be rectified. Rectification can be performed in several ways, however to create a smooth rebiasing voltage a full wave rectifier should be used. A full wave rectifier rectifies both the positive and negative parts of the AC signal, preventing DC voltages drops when the signal phase is negative. Full wave rectifiers can be built manually using a diode bridge (see Figure 21) and are also readily available as prebuilt bridge rectifiers. Vacuum tube rectifiers are also available. Vacuum tube rectifiers are large, expensive, and sag in voltage during high current operation, making them unfavorable when compared to solid state rectifiers.

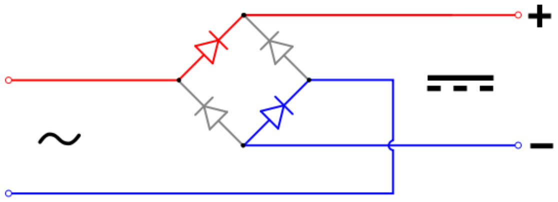


Figure 24: A schematic view of a diode bridge

The rectified output rebiasing circuit offers a simple, low cost solution that operates continuously and manages to use the AC signal while obviating any issues related to signal phase. The signal, however, must travel through the entire circuit before rebiasing is performed. This can create some response lag in the rebiasing process. There can also be drops and jumps in signal bias when input signals are very dynamic. These jumps and drops can be countered by adding a capacitor to the rectifier output; this however further slows the response time of the circuit and limits the touch sensitivity of the circuit.

Strengths: Fairly simple, fairly low cost, continuous rebiasing, no phase issues

Weaknesses: Very slow response time, added parts

Global Negative Feedback Loop

One way to obviate the slow response time is to avoid the use of a rectifier and use the AC signal directly. It is not possible, however to use the AC signal to rebias the vacuum tube. The AC signal can, however, be used to negatively interfere with the original AC signal. In order to create negative interference, instead of positive interference, the phase of the signal must be inverted. The inverted output signal can then be fed back into the input signal in order to create negative interference. This is a common technique in guitar amplification known as a global negative feedback loop. These loops generally takes the final output of a power amplifier, generally from the output of an output transformer, and feeds it back into the input of a pre-amplifier. This offers the advantage of not requiring any rectifier or capacitor smoothing, slightly decreasing response time, cost and complexity. Global negative feedback loops, however, still are global devices which must travel through the whole amplifier, limiting response time. This becomes an issue when the output signal and input signal must be in phase with each other. These loops also require phase inversion, which is already present in push-pull amplifiers but not in single-ended amplifiers. Global negative feedback loops have a large effect on frequency response, both flattening and extending it. Many circuits that employ negative feedback loops comprise tone circuits added specifically to accentuate frequency ranges that have been dampened by the negative feedback loop.

Strengths: Very simple, very low cost, continuous rebiasing

Weaknesses: Require phase inversion, frequency effects, phase issues, response time issues

Single-Stage Inverting Feedback Loop

One way to obviate the slow response time and phase issues of the global negative feedback loop is to use a local feedback loop. Although far less common than global negative feedback loops, single-stage inverting feedback loops are sometimes used to avoid the problems of global negative feedback loops. These loops use a single vacuum tube amplification stage which inverts the signal and feeds it back instantly to the input of the stage. This offers very quick response time, helping solve any issues with response time and phase. The use of a single-stage inverting feedback loop alters the design process of the amplifier drastically, creating a design with very different properties than a standard common-cathode amplifier (the standard per-amplifier design.) The effects of these difference include gain which is independent of tube parameters, fixed input impedance, very low output impedance, a flat and broad frequency response (similar to a global negative feedback loop) and extremely high linearity.

Strengths: Very simple, very low cost, continuous rebiasing, low response time, minimizes phase effects

Weaknesses: Require phase inversion, frequency effects

Attenuated Common-Cathode Triode

One alternative to over-distorting the signal and then correcting it is to avoid distorting the signal. Operating at low voltages creates a smaller range of linear operation, but by attenuating the input signal it is theoretically possible to scale the input voltage to work within this range. This offers the advantage that the output of the circuit can remain untouched, obviating the compressive effects of most other circuit types. It also allows the usage of the common-cathode triode as the basis of the circuit, providing a circuit which has well characterized behavior and is generally considered aurally pleasing. While the circuit is well known, the low voltage operation does create some design issues and the attenuation is highly theoretical, providing issues in implementation.

Strengths: No compressive effects, simple, low cost, well characterized

Weaknesses: Theoretical, possibly difficult to implement

DC Coupled Cathode Follower

Most forms of negative feedback discussed use the output signal itself to provide negative interference with the input signal. The DC coupled cathode follower uses a very novel approach which differs from previously discussed negative feedback systems in both mode of operation and sound. As seen in Figure 23, DC coupled cathode follower uses two identical triodes. The first triode is wired for common cathode operation, the most common triode circuit. The anode voltage of the first triode, however, is fed directly into the grid of the second triode. The circuit is specifically designed so that this plate voltage causes the second triode to draw grid current. This current is taken from the anode of the first triode, causing a voltage drop. This voltage drop instantly lowers the bias of the first triode, decreasing the signal strength. In this sense, the DC coupled cathode follower essentially acts as a simple compressor which responds almost instantly. Low power signals will create small grid current draws in the second triode, essentially limiting the compression effects to only the desired signals. The DC coupled cathode follower is very linear, low cost, simple and produces a very distinct distortion sound which is fairly compressed, being described as "smooth" and "crunchy" as opposed to "fizzy." There is some inherent gain loss, but circuit variations exist which can minimize this. The DC coupled cathode follower also suffers from very low input impedance, leading to potential blocking distortion, when standard design techniques are applied. It may be possible to use non-standard design techniques to obviate this problem.

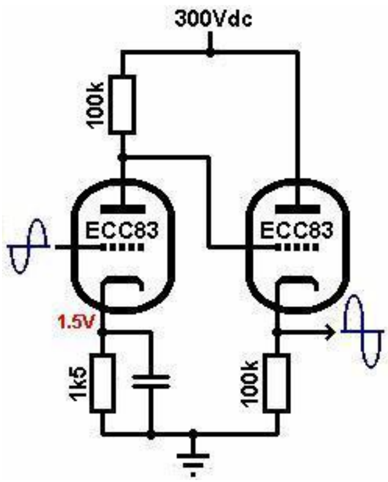


Figure 23: DC Coupled Cathode Follower (Blencowe, The DC Coupled Cathode Follower, 2011)

Strengths: Very simple, very low cost, very linear, maintains gain levels

Weaknesses: Distinct sound and compressive effects may not be universally liked, low input impedance

AC Coupled Cathode Follower

The AC coupled cathode follower remedies the impedance problems of the DC coupled cathode follower. The output signal is taken from the cathode, similarly to the DC coupled cathode follower. This signal, however, isn't coupled to any other gain stage, thereby limiting the voltage gain to unity. Furthermore, the load resistance is designed to provide perfect negative feedback, removing all non-linearity from the signal. In essence, this removes all distortion from the gain stage. In a sense, the AC coupled cathode follower acts as a buffer, providing desirable impedance characteristics while being completely transparent.

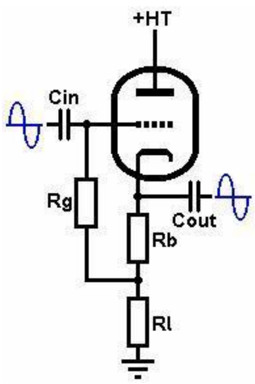


Figure 24: AC Coupled Cathode Follower (Blencowe, The AC-Coupled Cathode Follower, 2011)

Strengths: Very simple, very low insertion loss, very low cost, very linear, high input impedance

Weaknesses: Tonally transparent, zero gain, provides very little distortion

Mu Follower

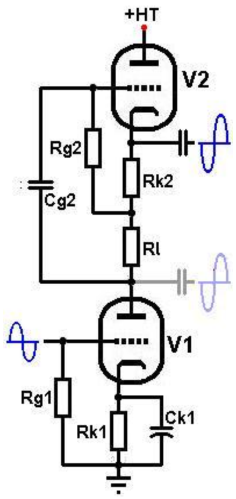


Figure 25: Mu Follower (Blencowe, The Mu-Follower, 2011)

The mu follower remedies the lack of gain and distortion of the AC coupled cathode follower by tying it to a standard triode gain stage. This not only adds the tonal characteristics of the first gain stage, but introduces a dynamic load. This dynamic load creates a very unique and distinct distortion which is known to be very rich in both odd and even harmonics. This corresponds to a sound with both pleasant and unpleasant aural characteristics. The mu follower still maintains some of the benefits of the AC coupled cathode follower, including a good range of linear behavior, but loses many of the benefits, including input impedance and insertion losses.

Strengths: Simple, low cost, high gain, very linear, high harmonic distortion

Weaknesses: High input impedance, distortion can be unpleasant

Cascode

The cascode is commonly seen in guitar amplifiers but rarely seen in distortion pedals. The cascode uses two gain stages. The first gain stage is a standard triode gain stage. The anode of the first gain stage is tied directly to the second gain stage. This sets the load resistance of the first gain stage equal to the very low cathode impedance of the second gain stage, lowering the gain of the first stage dramatically. The grid of the second stage is biased directly using an outside voltage source, often a voltage divider off of the plate voltage source. The interaction between the gain stages creates a pentode like behavior and sound characteristic. As such, it provides very high gain, very low input capacitance, but does not suffer from the noise problems inherent to the pentode. The pentode like behavior does little to rectify problems with linearity.

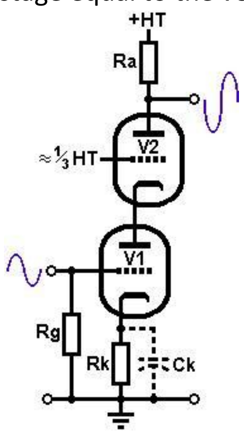


Figure 26: Cascode (Blencowe, The Cascode, 2011)

Strengths: High gain, high input sensitivity, very simple, very low cost

Weaknesses: Not very linear, pentode-like behavior bad at low voltages

7.4 Circuit Concept Selection

Similarly to the vacuum tube scoring, the circuit concept scoring matrix was a direct translation of the design requirements. Again, certain design requirements, such as size, availability, robustness and attractiveness were ignored for the purpose of the scoring process, as they were not relevant to the circuit design. Novelty was not included, as the importance of novelty was generally tied to user perception. Since the user would not see the circuit, its actual novelty was deemed irrelevant. Distortion sound quality was again the product of several different factors, which differed from those identified in the vacuum tube model. Each circuit type not only had a range (headroom) and degree (linearity) of linearity, but also had a sound characteristic (distortion quality) when the circuit was driven beyond its linear range. These factors were largely unknown, and hard to objectively assign numerical scores. While general information was available about the headroom, linearity and distortion quality of circuit types, these were usually subjective verbal descriptions of circuits operating at high voltages. Scores were generally assigned using these subjective descriptions as information sources. As many sources were consulted as possible and special note was made to any superlative descriptions.

Table 4: Circuit type concept scoring matrix

	Weight	Single-Stage Inverting Negative Feedback	Global Negative Feedback	DC Coupled	Attenuated Common Cathode	Cascode	AC Coupled	Mu Follower	Rectified Output Rebiasing	Zener Diode Network Rebiasing	Solid State Compression
Distortion	10	9	8	10	10	8	2	10	8	6	10
Touch Sensitivity	10	7	8	7	10	4	9	9	8	4	8
Novelty	3	4	3	8	8	5	8	8	6	10	5
Linear Range	4	9	10	10	10	10	10	10	5	5	2
Gain	5	5	4	8	10	10	1	8	3	2	8
Cost	9	10	10	10	10	10	10	10	10	10	7
Total	410	323	319	364	404	315	269	384	303	250	306

The results of the circuit design Kesselring matrix reveal the Attenuated Common Cathode to be the highest scoring concept. This is mainly due to its extremely high linearity, and high distortion quality. While many of the other circuits, such as the DC Coupled Cathode Follower and the Mu Follower, provide pleasant distortion, the lack of compressive effects in the highest scoring solution maintain high touch sensitivity and gain. Every other concept, in fact, introduces some form of compression, which in turn reduces gain over a certain range of inputs. This is made apparent by the fact that no single concept scored high as the Attenuated Common Cathode in terms of gain or touch sensitivity. The small number of components used in the Attenuated Common Cathode produces a low cost circuit by providing low costs for both parts and labor in assembly. Most of the drawbacks of the circuit were in its experimental manner and potentially difficult implementation. The Kesselring matrix, however, does not consider these as it is a mere translation of user needs and market requirements. The methodology selected was used in order to create a direct link between final product and user needs; in this sense the Kesselring matrix performed its function by ignoring implementation issues.

7.5 Concepts: Enclosures

The enclosure conceptualization process was limited by several requirements. Perhaps the most limiting requirement imposed was the usage of a standard enclosure, as opposed to a custom enclosure. The use of an off-the-shelf part not only ensures availability, but reduces costs and quality considerations. This limited the concept availability to commercially available parts. Within the realm of commercially available parts, another limitation was the ability to ground the circuit to the enclosure. As such, the enclosure had to be conductive, eliminating any plastic enclosures from consideration. Metal enclosures also provide RF shielding, preventing stray signals from being picked up by the low voltage and current circuit. Several enclosures described within were identified as both commercially available and suitable candidates for the application.

Hammond 1590B

The Hammond 1590B is a commonly used small footprint enclosure made of die cast aluminum. Although not available in small quantities from the manufacturer, it is universally available from both general and specialty part suppliers. It is fairly low cost, was identified as having a desirable size in the user needs study, and is considered moderately attractive. Although it is easily painted, its shape is considered to be generic and it offers very little novelty. The Hammond 1590B's desirably small footprint comes at the cost of volume; it is spacious enough to house the distortion sound effect but may not be spacious enough to house future products.

Figure 26: The Hammond 1590B

Strengths: Size, cost, availability

Weaknesses: Generic appearance, limited space

Hammond 1590BB

The Hammond 1590BB is another commonly used enclosure made of die cast aluminum. It is similar to the 1590B in both cost and availability. It differs, however, in its footprint and shape. The 1590BB has a larger footprint, making it larger but providing more internal volume. Many users found the 1590BB to be slightly too large, however most accepted it is a standard sized product. The larger footprint slightly increased the enclosure's perceived robustness. The 1590BB has less sloped sides, which most users found to be less attractive than the 1590B.

Figure 27: The Hammond 1590BB

Strengths: Cost, availability, robustness

Weaknesses: Generic appearance, size

Pedalenclosures YY

Pedal Enclosures is a specialty supplier of guitar sound effects enclosures. The YY is their smallest offering, having a similar footprint to that of the Hammond 1500BB. The YY differentiates itself with its appearance, having a distinct and attractive looking sloped design. This sloped design provides an angled surface for

Figure 28: Pedal Enclosures YY

user interfaces, which can slightly improve ease of use. The sloped design and large rubber feet make the product both appear robust and provide stability during use. The YY is only available from one supplier and at a price that is appreciably higher than that of the Hammond enclosures.

Strengths: Attractive, robust, easy to use, distinct looking

Weakness: Only one supplier, high cost

Hammond 500

The Hammond 500 is another enclosure incorporating a sloped design, providing a more attractive solution that is easier to use. The Hammond 500 is made of thin bent steel, providing a lower weight enclosure than the previously mentioned cast aluminum enclosures. Users, however, indicated, that they prefer a heaver enclosure, as it appears more robust and is more resistant to motion during use. The steel enclosure is powder coated in light grey. This saves the step of painting, but also dictates what color the enclosure will be. The powder coating should make the plain steel resistant to rusting, but not completely immune, especially if the power coating is worn during usage. The Hammond 500 comes in several sizes, all of which being slightly larger than what users indicated to be desirable.

Figure 29: The Hammond 500

Strengths: Powder coated, easy to use, attractive, distinct looking

Weaknesses: High cost, possible rust issues, lighter weight, difficult to implement, large

7.6 Enclosure Concept Selection

The enclosure scoring matrix can be seen in Table 5. The scoring categories and weights were directly translated from the design requirements. Looking at the relevant characteristics, we see that many are based on user perception and can be very subjective. This created difficulties in assigning accurate scores in an objective manner. When possible, user statements based on existing solutions were used in order to assign scores. Both the Hammond 1500B and 1500BB are commonly used enclosures and many users commented on their attractiveness. The use of subjective judgments was unavoidable, however, when assessing the attractiveness and perceived robustness of novel enclosures. When possible, trends in user perception were used as scoring guidelines.

Table 5: Enclosure concept scoring matrix

	Weight	Pedal Enclosures YY	Hammond 1590BB	Hammond 1590B	Hammond 500
Cost	9	3	10	10	3
Robustness	5	10	9	9	6
Novelty	3	10	1	1	6
Size	3	9	8	10	8
Availability	7	4	10	10	7
Attractiveness	7	10	6	7	8
Total	340	231	274	287	204

Sloped surfaces, for instance, were identified as attractive in the user needs study, leading to high attractiveness scores for the YY and Hammond 500. Heavier enclosures were perceived as more robust, leading the low robustness score for the Hammond 500. Several other scoring categories, such as size and cost, provided for simple and objective scoring. Looking to the scoring matrix of table 5, we see the Hammond 1500BB to be the highest scoring solution, scoring slightly higher than the YY. This was mainly due to its greater availability and lower cost. As the highest scoring solution, the 1500BB was selected as the product enclosure.

7.7 Concepts: Vacuum Tube Protection

The Hammond 1590B enclosure selected does not contain enough internal space to house the vacuum tube within. Furthermore, it may be undesirable to house the vacuum tube within the enclosure, as this may hide the fact that the product implements a vacuum tube for amplification. As such, the tube must be mounted externally to the enclosure. Product robustness was identified as a key user requirement. It is common practice to provide some sort of protection for externally mounted vacuum tubes in order to provide protection. Similarly to the enclosure selection, it was deemed desirable to use a standard protection frame for the purpose of ensuring availability and reducing cost and quality considerations. While tube protection frames are a specialty part, having very few modern applications, several potential options were identified

Standard Protection Frame

Stand-alone amplifiers almost universally implement what has become a standard tube protection frame (see Figure 30.) Due to their common usage, they are widely available at a low cost. This frame mounts to the vacuum tube socket with a bayonet mount and contains an internal spring to isolate the vacuum tube from shock and prevent movement. The standard tube protection frame is extremely robust, although may not be perceived as such as it is made of thin metal and completely obscures the vacuum tube. While these frames are commonly used in stand-alone amplifiers, they are usually mounted internally. Users stated that they found the standard vacuum tube protection frame to be unattractive.

Figure 30: Standard tube protection frame

Strengths: Cost, availability, actual robustness

Weaknesses: Perceived robustness, attractiveness

Damper Ring

One specialty device used to protect vacuum tubes is the damper ring. The damper ring, however, is better served at protecting the vacuum tube from vibrations which can cause distortion as well as a microphonic behavior. Although the damper ring offers very little actual robustness, users did perceive the damper ring as providing some robustness. The damper ring is a low cost device which was identified as being considered fairly attractive. Very few products implement a damper ring for an externally mounted vacuum tube, making it a novel solution which would create product differentiation. The damper ring is available from several source, although not nearly as many as the standard protection frame.

Figure 31: Damper rings

Strengths: Cost, novelty, vibration damping

Weaknesses: Actual robustness

Die Cast Frame

There are some commercially available tube protection frames. One such product is a die cast aluminum frame as seen in Figure 32. This frame is extremely robust, both in appearance and in performance. No other solutions on the market implement it and it provides a distinct and attractive look while letting the user clearly see the vacuum tube during operation. This attractiveness and robustness come at a significant cost however; the die cast aluminum frame has a much higher price than other solutions and is only commercially available from one suppliers.

Figure 32: Die Cast Frame

Strengths: Attractiveness, robustness, novelty

Weakness: Only one supplier, high cost

Ring Frame

Another commercially available specialty frame is the ring frame. The ring frame consists of three silver plated brass rings separated by standoffs. The ring frame itself is a fairly low cost device which mounts directly to the enclosure via three screw holes. It appears very robust, although its open structure makes it slightly less robust than the standard tube protection frame. No other solutions on the market implement it and it provides a distinct and attractive look while letting the user clearly see the vacuum tube. It is commercially available from very few suppliers.

Strengths: Novelty, attractiveness, perceived robustness, fairly low cost

Weaknesses: Limited number of suppliers

Figure 33: Ring frame

No Protection

One final option explored was not providing any form of protection for the vacuum tube. This offered a clear advantage in that it would provide a zero cost solution to the problem. Furthermore, the solution would not require any supplier, completely removing bargaining power of any potential suppliers. This solution would also clearly display the presence of the vacuum tube by displaying the exposed device and its glowing filament. The use of no protection frame, however, does not solve the problem of protection. This has no apparent robustness and many users said they would be unwilling to purchase a product that had no vacuum tube protection.

Strengths: Cost, availability

Weaknesses: No perceived robustness

7.8 Vacuum Tube Protection Concept Selection

The vacuum tube selection scoring matrix is presented in table 6. The scoring categories and weights were directly translated from the relevant design requirements. Similarly to the enclosure scoring matrix, scores were largely based on subjective judgments. When possible, user statements were used as scoring guidelines. The use of no tube protection frame, for instance, was brought up during user interviews and was explicitly stated as being not robust enough to implement. The standard tube frame, as well, was brought up in user interviews and was considered to be fairly unattractive. Many of the scores for other solutions and categories, however, were made based on subjective judgments. These judgments, however, were made in a systematic framework; as such the matrix was considered an accurate tool for making an informed design decision based on user needs. The scoring matrix reveals the ring frame to be the high scoring concept and thus was selected for the vacuum tube protection method.

Table 6: Vacuum Tube protection concept scoring matrix

	Weight	None	Standard	Die Cast	Ring Frame	Damper
Cost	9	10	6	3	4	8
Robustness	5	1	5	10	8	3
Novelty	3	3	1	10	8	5
Availability	7	10	9	1	3	5
Attractiveness	7	5	1	9	9	7
Total	310	209	163	96	256	174

7.9 Design Conclusions

The concept selection processes each contained a single solution which scored appreciably higher than the other solutions. This provided clear decisions which were direct translations from the design requirements. The fact that the design requirements were directly translated from the user needs study provided for confidence in the results of the concept selection process. The subjectivity that appeared when assigning scores did add some subjectivity into what was envisioned to be a structured and objective process. This subjectivity was deemed to be inevitable, however, and it was dealt with in the most objective way possible. The usage of such resources as user opinions aided in selecting solutions which would please users in spite of the lack of objective scoring.

Although the Kesselring matrix does a good job of scoring concepts based on user need fulfillment, it was only used within that scope. Auxiliary issues, such as difficulty in implementation, were not accounted for in the matrix. A category could have potentially been created to account for this, but it was deemed to be a separate concern, outside of the scope of the Kesselring matrix. Furthermore, difficulties arise when assigning weights of internal concerns, such as producability in comparison to market concerns, such as attractiveness. The purpose of using the Kesselring matrix was to provide a tool which would ensure the selected concept would be directly translated from design requirements, allowing for transparent design traceability. In this sense, the Kesselring matrix served its purpose.

8 Detailed Design

8.1 Vacuum Tube Circuit

The circuit to be used will be a variation of a dual stage common-cathode triode amplifier. This is the most commonly used tube amplification stage. (Aiken, 2010) In order to design a common-cathode triode amplification stage, we must first select an anode resistor. This resistor dictates the current response of the anode based on output voltage. As the resistor is a linear device, the resistor is simply represented as a line on the graph between voltage and current, as can be seen in Figure 34. If too large an anode resistor is selected then small changes in grid voltage create large changes in output voltage, creating a circuit which is too easily driven to non-linear operation. Furthermore, for a fixed grid voltage a large anode resistor corresponds to lower gain. If too small of an anode resistor is used then large changes in grid voltage create small changes in output voltage, creating a circuit which is not responsive. Furthermore, the usage of a small anode resistor risks exceeding the power output capabilities of the vacuum tube. An anode resistance of 150kΩ has been plotted in Figure 34. Should we assume a maximum input voltage of 2V with 90% attenuation, we will have a grid voltage swing of 0.2V. A visual inspection shows that this provides a good balance between voltage swing, linear behavior and voltage gain.

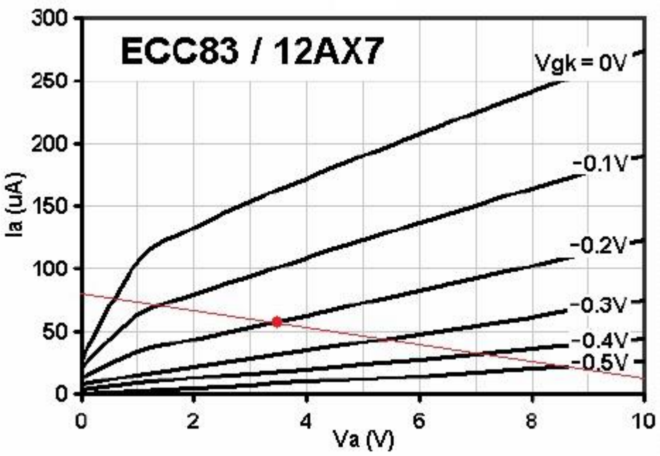


Figure 34: Load line analysis of the first triode stage

With the anode resistance set, the next step is to set a bias point. The bias point is a center point which the gain stage will operate at when no signal is applied. This is essentially done by setting the grid at a negative voltage relative to the cathode. Knowing that our grid voltage swing is 0.2V, we can set our bias voltage to -0.2V, producing a voltage swing which should never operate at cut-off or grid conduction. There are several ways to set this bias. This bias is typically set using a cathode resistor, which connects the cathode to the grid. Operating at low anode voltages essentially lowers the grid resistance. This lower resistance grid now conducts a small amount of current, acting as a constant current sink. Grid-leak bias is another commonly used method, although is generally unusable at low anode voltages due to issues with impedance mismatching. Consequently, the only way to bias the grid is via direct voltage application. (Blencowe, Triodes at Low Voltages, 2010) One potential alternate method of biasing the gain stage is to use a pull-up resistor. This method uses a resistance to connect the grid to the supply voltage. Since the supply voltage is significantly higher than the cathode voltage, this allows for a much higher resistance given a fixed grid leak current. To calculate the size of the pull-up resistor, a bias voltage must be chosen. For the current application a bias voltage of -0.2V has been selected. In order to size the resistor, the corresponding grid current is found using the graph of Figure 35. This resistor must drop the 12V source voltage plus the 0.2V bias voltage, for a total of -12.2V. The current that that grid requires can be found using the graph of

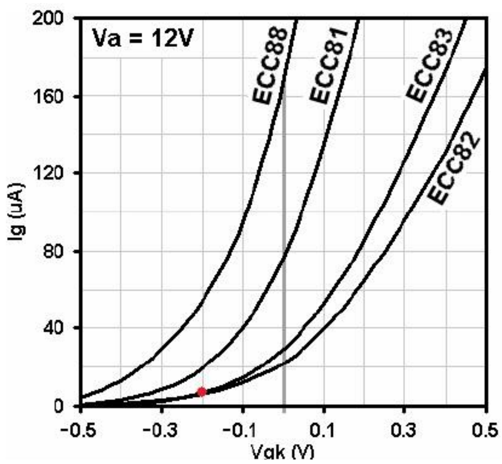


Figure 35: Grid current response of first gain stage

bias voltage against grid current at an anode voltage of 12V. This graph can be seen in Figure 35, where a mark has been made at the appropriate bias voltage. The corresponding grid current is 12uA. Using Ohm's Law, the appropriate pull-up resistor is found to be 1MΩ.

The first gain stage requires an attenuated input signal. The use of a pull-up resistor means that a simple resistance based voltage divider cannot be used, however, as it would provide a path between power and ground. Consequently, a circuit must be created that will not provide a path between DC bias of the grid and ground, but can attenuate the AC input. A capacitor based device is ideal for AC transparency and DC blockage. In order to deal with this specific problem, a capacitive attenuator was theorized which would operate as a reactive inductive voltage divider to the input signal while blocking the path between the grid and ground. Each capacitor has a reactive inductance equal to:

$$Z = \frac{1}{2\pi f C}$$

Since the goal of the circuit is to drop about 90% of the signal to ground, and reactive inductance is inversely proportional to capacitance, the output capacitor should be approximately 9 times larger than the input capacitor. This will provide an impedance that is 9 times lower, thereby creating a 10% voltage drop. Knowing the ratio of the capacitances, they must simply be sized. One requirement in sizing the capacitors is that they needed to be commonly available non-polarized capacitors (non-polarized as grid current could lead to reverse flow.)

The attenuation capacitors would also affect the frequency response of the circuit. The capacitances and resistances of the circuit essentially create a series of high pass and low pass filters which dictated the frequency response of the circuit. The first stage essentially contains a high pass filter created by the attenuator and a low pass filter created by the tube's internal capacitances. In order to assess the frequency response, these filters were modeled. Standard capacitor values were placed in the model and the results were visually inspected. The user needs study revealed that users were interested in a versatile product. As such, the goal was to have a flat frequency response over the range of guitar frequencies, generally around 80Hz-1200Hz. After testing all feasible combinations of standard capacitors, the combination of capacitances which produced the best frequency response was identified to be 100nF and 10nF.

Using several capacitors as an input creates an input impedance that varies with frequency. Input impedance is not of particular impedance, unless it drops significantly. Operating at low voltages, as previously mentioned, lowers the effective grid resistance. Should the attenuator also have a low impedance, the input capacitance of the device will be very low. This low input impedance can attempt to draw current from the source, in this case the electric guitar pickup. Electric guitar pickups have extremely low currents, making them unable to provide this current. This leads to a signal cutting out, also known as "blocking distortion." In order to investigate whether the input impedance would be a problem, impedance response of the

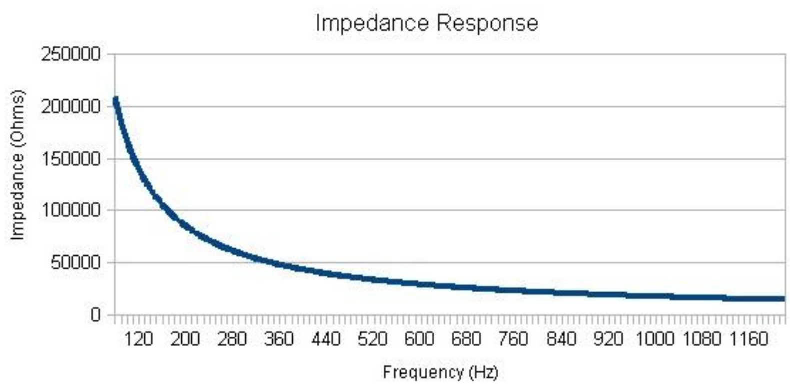


Figure 36: Impedance response of the attenuation circuit

attenuator to frequency was calculated and can be seen in Figure 36. It becomes apparent that there is indeed a large change in reactive impedance based on the frequency input. This change is not a problem as long as the impedance is always relatively high to that of a guitar pickup. Most electric guitar pickups have an impedance of around 8kΩ, while the minimum impedance of the attenuator over the range of electric guitar frequencies is over 14000Hz.

Even though we expect the input to each gain stage to be pure AC signal, stray DC voltages can be present. Similarly how the circuit employs a capacitor as a method to block the path of the grid voltage to ground, capacitors are commonly used in order to block any DC voltages from entering or leaving each stage of the circuit. These capacitors are commonly known as coupling capacitors, as they are used to couple circuits and parts of circuits together. The signal attenuator blocks DC voltage from entering the circuit, so coupling capacitors must be added to the output of the first gain stage and the output of the overall circuit. The inter-stage capacitor works in conjunction with the output resistance of the first stage to act as a high-pass filter, while the output capacitor works in conjunction with the output resistance of the second stage to form another high-pass filter. These capacitors were sized to be 100nF in order to match previously used values and were included in frequency simulation. The overall results of the frequency simulation can be seen in Figure 37. This includes the effects of the attenuator, coupling capacitors and internal capacitances of the vacuum tubes.

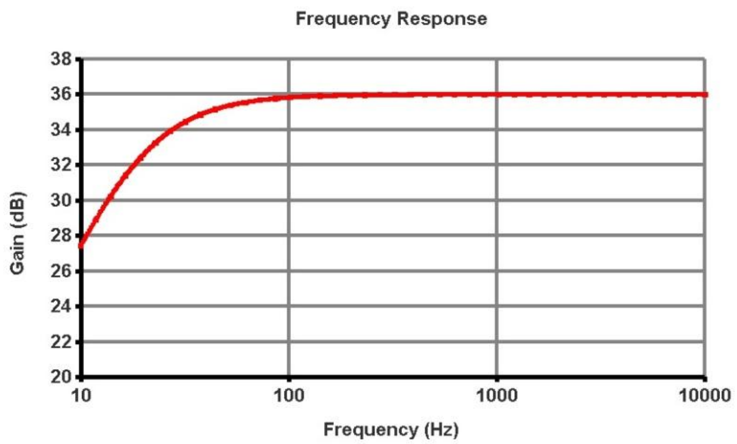


Figure 37: Frequency response of the circuit

Looking at the frequency response of Figure 37, we see a gain of about 35.5dB. Electrical gain is dictated by the following equation: $G = 20\log\left(\frac{V_o}{V_i}\right)$. Solving for V_o, we find it to be equal to 11.5V. The load-line of Figure 36 shows grid conduction limiting the voltage to a maximum of 0.5V, while cut-off limits the voltage to 12V, corresponding to an output voltage swing of 11.5V. This confirms accuracy of both the principles and the frequency simulation. This level of voltage gain is also extremely similar to the initial gain stages of many high voltage dual common-cathode triode amplifiers. This confirms that the scaling down of the input indeed scales down the output.

This 11.5V output signal serves as the input signal to the second gain stage. This swing in input voltage will cause non-linear distortion of the signal regardless of anode voltage. This is not necessarily a bad thing, however, as the goal of the circuit is to add distortion to the signal. The circuit itself was initially conceptualized to behave in an identical manner to a high voltage dual common-cathode triode amplifier; that is to say that the first gain stage should provide voltage gain and the second gain stage should respond non-linearly due to this voltage gain. As such, we do not want to re-attenuate the output signal, as it is already at 10% of the output signal of most high voltage dual common-cathode triode amplifiers.

There are two commonly used methods for setting the second anode resistor, either using the same value as the first anode resistor or using a value that is half that of the first anode resistor. Using a smaller value creates a steeper load-line. This steeper load-line corresponds to less gain, as the voltage swing at the output is lower. Using the same value as the first stage creates a less steep load-line, which corresponds to more output voltage swing, creating a gain stage which will have less more. There are, however, benefits to a smaller anode resistor, mainly related to the distortion content. A lower load resistance produces richer harmonic distortion content, particularly even harmonics, which are generally considered to be aurally pleasing. (Blencowe, 2009) A clear tradeoff was present between gain and distortion quality. Due to the low gains associated with low voltage operation, the anode resistor was selected to be the same size as the first stage. Should gain found to be adequate during testing or distortion content found to be too low, lowering this value would provide a simple method for increasing distortion content. A load-line for the second gain stage was plotted as can be seen in Figure 38.

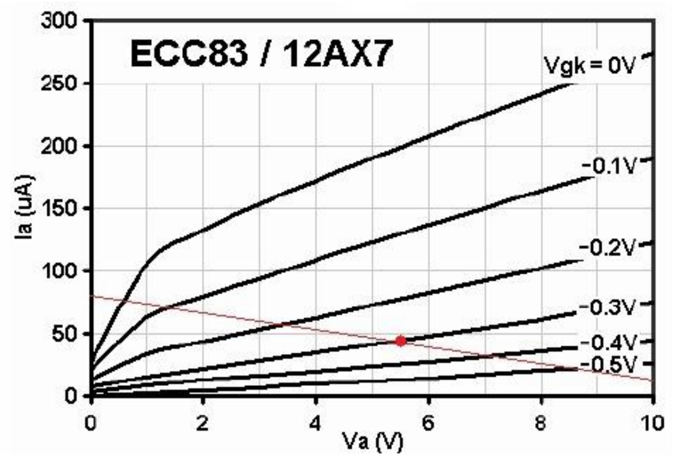


Figure 38: Load line analysis for second gain stage

The second gain stage will distort the signal due to the significantly high input signal. This fact changes the biasing considerations, instead of biasing to avoid distortion we must instead bias to shape the distortion. In general, cut-off distortion is considered to be more aurally pleasing than grid conduction distortion, providing a harder sound which is generally associated with distortion sound effects. Biasing toward cut-off means a more negative grid voltage, consequently a grid voltage of -0.3V was selected for the second gain stage. For the same reasons as in the first gain stage, a pull-up resistor was used to bias the second gain stage. The voltage drop across the pull-up resistor will again be the difference between the -0.3V grid and the 12V power supply, equaling 12.3V. Looking at the graph of Figure 39, we see that the grid current is equal to 6uA. Using Ohm's law, we calculate the resistor size to be 2MΩ.

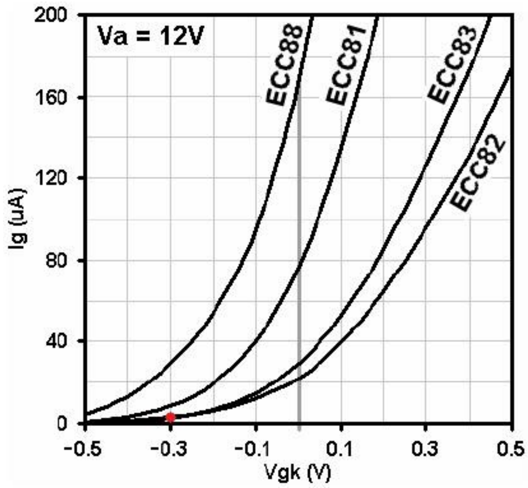


Figure 39: Grid voltage response of second stage

One further theoretical method was employed in the second gain stage in order to improve linear behavior: the addition of a grid-stopper resistor. A grid stopper resistor is a resistor placed directly before the grid of a vacuum tube, commonly used to reduce blocking distortion and control the frequency response of a circuit. This resistor connects to the grid, which experiences conduction when the negatively biased grid is driven positively. The grid current of the second stage is non-linear. Putting a resistor in the path of the grid current creates a voltage, which will increase as grid current increases. This voltage is added to the input signal to the grid, thereby creating a voltage increase at the input as signal strength increases. Increasing the voltage of a grid that is biased towards cut-off essentially rebiases the grid toward center bias, reducing distortion slightly as input signal increases. Voltage is dropped across the resistor, so a low resistance of 1kΩ was used in the initial design in order to prevent signal loss. This value could theoretically be changed in future design iterations to either increase or decrease linearity at the expense of output signal strength.

With both gain stages biased there was only was only one issue remaining: user interfaces in the circuit. The majority of users stated that most products on the market offer too many controls. Most users rarely touch the tone circuit of their distortion pedals. The only widely used variable user interface was found to be the volume knob. Volume is almost universally controlled by a potentiometer which diverts a portion of the signal to ground. Volume controls in circuits are generally place at the output of gain stages. Placing the volume control circuit at the output of the first gain stage would affect the input to the second gain stage, where lowering the volume would lower the voltage swing and thus potentially change the distortion content. Users stated that they are not interested in altering the distortion content, but rather the volume. Due to this fact, the volume control was placed at the output of the second gain stage. A standard potentiometer value of 50kΩ was selected. This value is relatively small, having little effect on the output impedance of the circuit. Other necessary interfaces were a switch to bypass the effect and a switch to apply power to the effect. These were both included in the design of the circuit. The initial design of the circuit can be seen in Figure 40.

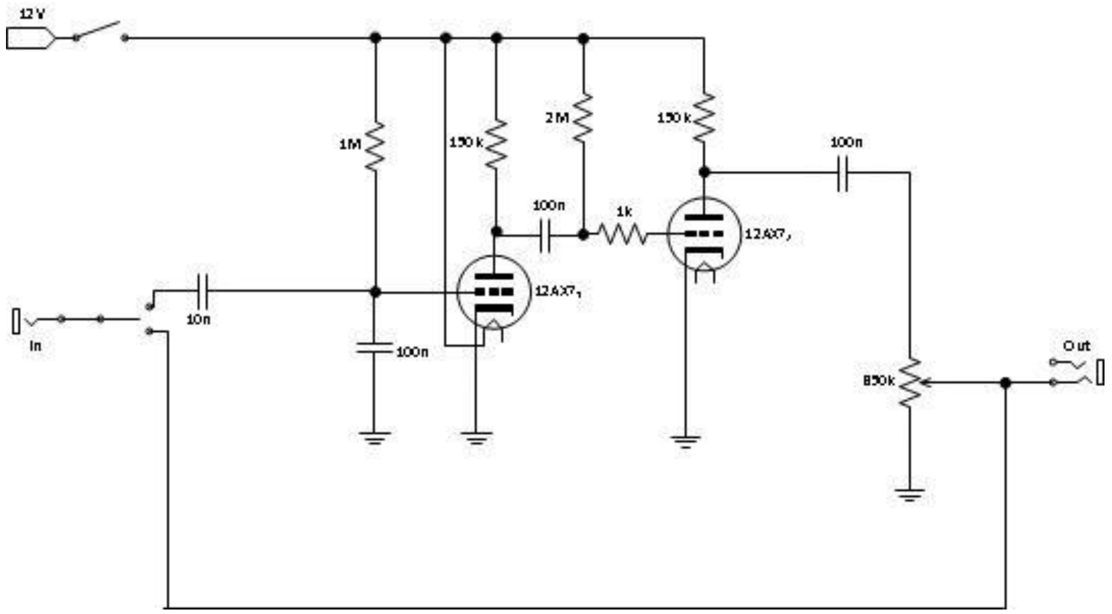


Figure 40: The initial circuit design

8.2 Enclosure

Before performing the detailed design of the enclosure, it was necessary to design the interfaces which would be housed on the enclosure. Two interface needs were identified during the user needs study, as discussed previously. Users needed to be able to activate and deactivate the sound effect without interrupting guitar playing and to adjust the amount of distortion quickly and easily in all lighting situations. Another interface requirement stems from the usage of a vacuum tube. Vacuum tubes themselves have limited lifespans and their filaments produce a faint glow when activated. As such, it was deemed desirable to include a master power switch interface for the vacuum tube. The product itself required several interfaces to communicate with other devices, namely a guitar input, an amplifier output and a 12V DC input.

Figure 41: Machined aluminum knob

The distortion adjustment interface needed to be attractive and simple to operate, particularly in poor lighting. This deemed out the use of conventional knobs with circular faces, as many users stated these were difficult to operate in low lighting. Some commercially available knobs provide small radially extending pointers to increase visibility and usability. Users stated that this increased ease of use in low lighting, but was unattractive. The machined aluminum knobs seen in Figure 41 were identified as both attractive and simple to operate in low lighting situations and thus selected as the distortion adjustment knob. Adjustment knobs are conventionally mounted on the top surface of the enclosure. This not only creates a crowded top surface, but places the adjustment knob near other interfaces where it can be accidentally adjusted. Due to this fact, the adjustment knob was moved to the side of the device.

The master power switch needed to be attractive, clearly communicate its method of operation, and be simple to operate, while preventing accidental deactivation. A push button switch on the side of the device was selected as a switch which was both simple to operate and difficult to accidentally deactivate. A red push button switch was selected so as to clearly communicate its function. A separate switch needed to be included to activate the sound effect. Other sound effects almost universally employ a stomp actuated push button switch for activation. These switches are low cost, widely available and well-liked by the users. As such, a standard stomp actuated push button switch was selected for operation, to be mounted on the top surface of the enclosure.

Guitar sound effects have standard location for external interfaces; the input jack is generally located on the right side of the device and the output jack is generally located on the left side of the device. The power jack is generally located next to one of the jacks. These locations were selected for the current product so that users have familiarity with product operation.

With the enclosure selected and interfaces designed, the only remaining issue was the painting and finish of the enclosure. With branding playing such a large role in purchasing decisions, the finish of the device would be very important in both communicating product qualities and creating brand recognition. The color of the device needed to communicate that the product is a professional quality device. It was also desirable to avoid colors that are commonly used in other guitar devices in order to create product differentiation and brand recognition. In order to achieve both of these, other audio devices, particularly hi-fi devices, were surveyed in order to observe any design trends. The results of this survey showed that premium audio devices have finishes that are generally either brushed aluminum, matte black or gloss white. Both matte black and brushed aluminum were identified as common finishes for guitar devices and thus deemed unsuitable finishes. Thus, gloss white was selected as the finish for the enclosure.

9 Prototyping

The design phase was followed by an initial prototyping phase. An effort was made to use eventual suppliers in part sourcing, in order to build supplier relationships and obviate problems in future product runs. Once the components were received, the circuit created in the design phase was initially prototyped on a breadboard in order to confirm operation and allow for simplified measurement, changes and troubleshooting. This proved to be useful as several minor problems required troubleshooting in the prototyping process. No user interfaces were included in the breadboard prototype as its purpose was to confirm circuit operation.

An enclosure was created (see Figure 42) according to results of the design phase. The drilling and painting of the enclosure was outsourced to an industrial enclosure supplier. This was done to avoid purchasing tooling and supplies to manufacture a part that was subject to future design changes. No problems were encountered in the outsourcing process.

Figure 42: The product enclosure

Once the enclosure was completed, the circuit was to be transferred to a new vacuum tube socket and mounted to the enclosure (see Figure 43.) This process was performed in three steps. First, all interfaces were mounted to the enclosure and were wired together. After that, the main circuit was soldered to the vacuum tube socket to create a signal amplification module. This module was then mounted to the enclosure and then connected to the interfaces. This process was performed in this manner to demonstrate and confirm the modularity of the product. Signal amplification interfaces could theoretically be created and then connected to various devices, such as power amplifiers or enclosures for distortion sound effects. The only mechanical interfaces connecting the signal amplification module to the surrounding product were two bolts on the vacuum tube socket. The only electrical interfaces connecting the signal amplification module to the surrounding product were connections for +12V, ground, input signal and output signal. While electrical quick disconnects could be used to expedite future modular construction, they were not included in the prototype. The modularity of the product is component-swapping in that different pre-amplification modules can be used and component-sharing in that the pre-amplifier can be used in alternate product. (Huang & Kusiak, 1998)

Figure 43: The completed first prototype

10 Testing

Testing of the initial prototype was performed by professional musicians previous interviewed in the user needs study. The prototype was brought to users in order for them to test the prototype in conjunction with their own equipment. A short interview was initially held to discuss their initial impressions of the prototype before usage based on aesthetic and visual properties. The user then tested the prototype on their equipment. This testing was closely observed in order to note any usage patterns or latent needs. Finally, a long interview was held in order to receive user feedback on the prototype itself. All of the interviews were held using no interview guide. This unstructured format was selected in order to avoid leading the interview in any direction. The goal of the interview process was complete openness and objectivity in user feedback.

10.1 Results

All test users identified similar product characteristics; although there were some disagreements as to whether these characteristics were desirable. The quality of the distortion was generally well received, confirming the general operation of the device as well as the bias points. The lack of compression compared to other vacuum tube based products created a sound which was described as “clear” and “open”. Some users, however, stated that the device was too geared towards “a heavy metal sound.” These users described the sound as “glassy” instead of “crunchy.” This type of sound hurt the versatility of sound, making it more of a niche product than desired. In general, the gain of the circuit was described as adequate. The headroom of the device was considered to be adequate for the most part, although a few users stated that it could be increased slightly.

Observation showed that users were easily able to use the product without any instructions. Users were able to power up the pedal and switch it on and off easily. Users stated that these two interfaces were simple and “easy to use.” Users stated that they liked both the aesthetic and functional features of the volume knob. Users stated that its unique form factor and location made the product appear “different.” Furthermore, users stated that the volume knob would be “easier to use on stage” than most current products'. Users did, however, find issue with the potentiometer and often spent large amounts of time making adjustments to find the right output level. Furthermore, users tended to set the product to relative low output levels, reflecting excess gain and compounding the volume adjustment issues.

The aesthetic aspects of the product were well received by users. Users described the product as “professional looking” and stated that the product looked “unique” and like a “premium product.” Users spoke particular well of the tube protection frame, stating that it “makes the product stand out” and “looks sturdy.” The enclosure and frame managed to protect the product during transportation and testing. The paint on the enclosure did receive some wear and scratches during the testing process. This, however, was not identified as an issue by users.

11 Design Iteration

11.1 Redesign

A design iteration was made to incorporate user feedback into what was intended to be a final design. The goal of the design iteration was to remedy the problems identified in the testing phase. The circuit was identified as lacking touch sensitivity and headroom. The volume knob was observed to be not responsive enough, requiring coarse adjustments at high volumes and fine adjustments at low volumes.

Test results indicated that the device was too geared towards “a heavy metal sound.” This sound is generally associated with odd order harmonics. As discussed in the detailed design of the circuit, applying a lower anode resistance generally increases the proportion of odd-order harmonics at the expense of gain. Since test results indicated that the gain of the device was considered to be adequate, the anode resistor was lowered to 75kΩ in the redesign. A load-line for this anode resistance has been plotted in Figure 41. The original bias point has also

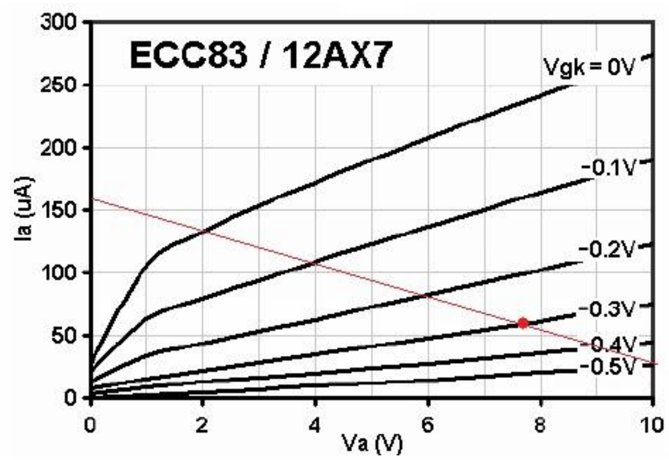


Figure 41: Load line analysis for redesigned second gain stage

been plotted on this load line. This bias point still appears to be appropriate, as the gain stage is still biased towards cut-off. Furthermore, the spacing between grid lines appears to be slightly more symmetric about the bias point, leading to a more symmetric output signal. This corresponds to larger and higher quality headroom. With gain equal to: $G = 20\log\left(\frac{V_o}{V_i}\right)$, the lower anode resistance of 75kΩ produces a gain of 34dB for the post-attenuated 0.2V input signal. This is only 1.6dB lower gain than the initial circuit design.

The source of the problems with the volume adjustment was identified as the potentiometer itself. A 50kΩ linear scale potentiometer was initially used as the volume adjustment. The problems associated with fine adjustments at low volumes and coarse adjustments at high volumes are associated the linear scale. Volume is a logarithmic function which is measure in dB. As such, the updated design replaced the 50kΩ linear scale capacitor with a 50kΩ logarithmic scale potentiometer.

The circuit after the design iteration can be seen in Figure 42. This updated circuit design includes the removal of the grid-stopper resistor to decrease linearity, the addition of bootstrapping to increase gain and a logarithmic volume potentiometer to improve volume adjustments.

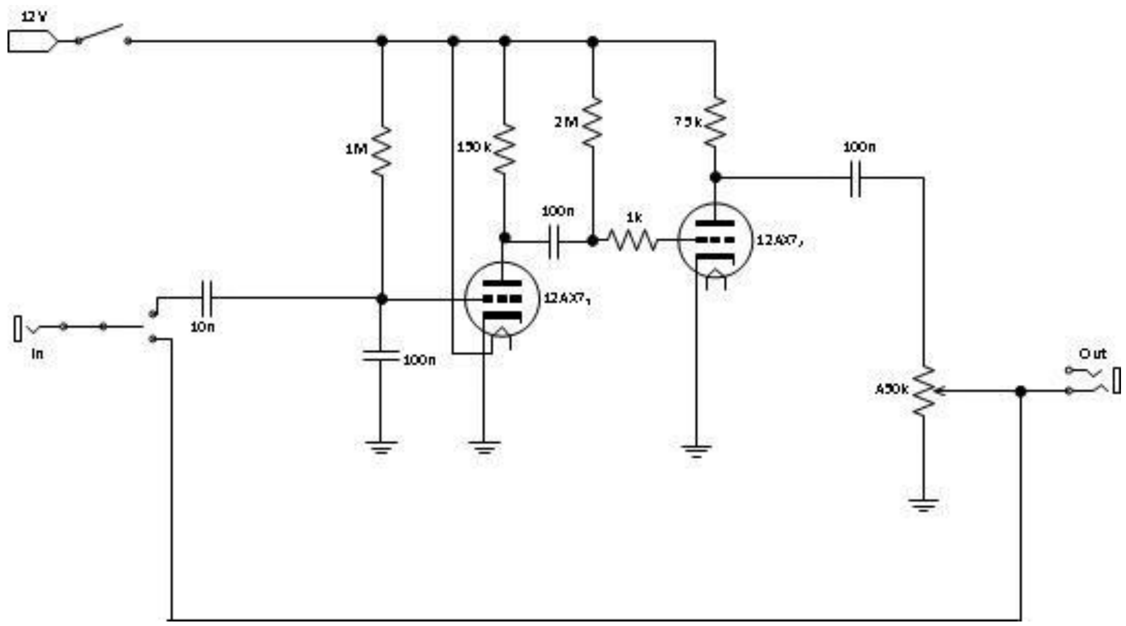


Figure 42: Updated circuit schematic after design iteration

11.2 Prototype Alterations and Testing

An updated prototype was created by making modifications to the existing prototype circuit. No aesthetic changes were made to the enclosure itself or the user interfaces. The only change to the user interfaces was a functional change made by replacing the potentiometer. All parts were sourced from the same suppliers as in the initial prototyping phase.

Lowering the anode resistance did a sufficient job of improving sound quality. The second prototype produced a sound that was less glassy and piercing, reflecting a higher proportion of even order harmonics. The less defined, “crunchier” sound came at the cost of gain. The second prototype did indeed have lower gain than the first circuit, although not a significant amount. The 1.6dB gain reduction caused by the lower anode resistance was noticeable, although its effects were neither large nor necessarily undesirable. As most users did not set the output level of the circuit very high, this essentially eliminated part of an unused adjustment area, thereby improving the volume control.

The change of potentiometer proved to further remedy the volume knob problems. While the volume knob problems were observed and not stated, simple usage tests revealed that test users were able to adjust the volume to the desired level more quickly than with the first prototype. This improvement was further confirmed by personal testing of the volume adjustment.

12 Intellectual Property

The inventive concept behind the circuit is the combined usage of a capacitive attenuator in order to reduce the input signal voltage proportionally to the smaller operating bounds associated with low anode voltage. The circuit biased using a pull-up resistor to provide a circuit that has a high input impedance to obviate blocking distortion and signal reflections. US Patent 5022305 describes the use of a pull-up resistor to provide high input impedance for low voltage vacuum tube operation. US Patent 7257382 describes the use of a network of capacitive attenuators at the input of a transistor in order to vary the gain of the circuit by attenuating the input. This patent, however, deals with the use of integrated capacitors in a switched gain setting for precise amplification control. Should the teachings of this patent be combined with US Patent 5022305, its benefits as described would not be present in the current application. As such there is no motivation to combine these references except for impermissible hindsight under MPEP 2145. As such, the references would not qualify as prior art under 35 U.S.C. 103 and the inventive concept resulting from this project is believed to be patentable.

Patentability aside, patents are rarely sought out in the guitar electronics industry, especially for vacuum tube devices. The cost of seeking patent protection is relatively high for a given device, and the risk of competitors making similar products is fairly low. The value of the patent, however, is partially in that it signals an inventive concept to users. This is perhaps more important when dealing with retail sales, as opposed to direct sales. The value of the patent also largely depends on the success of the product. Patent laws generally allow a one year trial period for a product to be sold on the market before applying for a patent. The use of a preliminary application can generally provide another year before a decision must be made. As such, no decision must be made about the pursuit of intellectual property rights at this time.

13 Extrapolation Plan

13.1 Pricing

The cost table was created to indicate the cost of the parts necessary to produce the product. Most suppliers offer discounts for bulk purchases. As such, costs have been included for product runs of 1, 10 and 100. The cost table includes outsourcing the drilling and painting of the enclosure, but does not include labor, which is expected to take 30 minutes per part. The cost table does not include costs of packaging, which generally consists of a small cardboard box.

Table 7: Cost table

Part	Quantity	Part #	Price 1	Price 10	Price 100	Source
R2M	1	0911K	0,02	0,02	0,02	Small Bear
R150k	1	0911K	0,02	0,02	0,02	Small Bear
R75k	1	0911K	0,02	0,02	0,02	Small Bear
R1M	1	0911K	0,02	0,02	0,02	Small Bear
C10n	1	1400	0,3	0,3	0,3	Small Bear
C100n	3	1400	0,3	0,9	0,9	Small Bear
12AX7	1	T-12AX7-S-JJ	9,75	9,75	9,75	Antique
A50K Mini	1	1011BM	1,4	1,3	1	Small Bear
Input	1	0602A	1,25	1,15	0,95	Small Bear
Output	1	0600A	1,15	1,05	0,9	Small Bear
DC Jack	1	611	1,25	1,05	0,8	Small Bear
Enclosure	1	1290NS	8,35	8,35	7,45	Pedal Parts Plus
AC Adaptor	1	GS06U-3P1J	13,65	12,95	8,44	Mouser
Knobs	1	813	1,55	1,5	1,3	Small Bear
Socket	1	P-ST9-400	1,15	1,15	1,15	Antique
Guard	1	CH-FM-39	5	5	5	Good Component
SPST	1	R13-548B-05-BR	1,64	1,64	1,14	Mouser
DPDT	1	204	3,75	3,5	2,75	Small Bear
Total			51,17	50,27	42,51	

The cost table indicates the potential cost savings of large product runs, as a product run of 100 costs approximately 20% less than a product run of 1. In general, the product costs are significantly lower than competitors prices, with the lower priced vacuum tube competitor being priced 50% higher than the cost of a product run of 1, while still performing worse. Based on feedback from test users, an initial feedback price of 80 USD will be set in order to attempt to penetrate the market. Both second degree and third degree price discrimination will be used, in order to provide lower prices based on order quantity and offer lower prices to key customers (professional users.)

13.2 Distribution

Most large retailers indicated in user interviews that purchasing decisions were made by corporate buying centers. Unsuccessful attempts were made to contact corporate buying centers. Smaller retailers, however, indicated that they would be open to product demonstrations and small stock purchases of products. The geographical sparseness and low product sales of small retailers, however, makes it unfeasible to demonstrate products to and distribute products through them. The user needs study indicated that most buyers both collect purchasing information and purchase products online. As such, direct online retail serves as an ideal venue for initial product runs.

13.3 Further Development

The initial intention of the project was to create a low voltage vacuum tube pre-amplification module, which could be used in a variety of products and to implement it into a distortion sound effect. Although this has been accomplished, there is potential for further development in several areas. The product itself has several design parameters which can be adjusted. Changing component sizes (such as the anode resistors) and adding components can drastically change the behavior of the product. Several features, such as adjustable tone, can also be easily added to the product. Further development exists in the form of creating several different product variations in order to meet user needs. These variations are all fairly simple and exploration of mass customization is a possibility for further development.

Another area of potential for further development exists in the form of further products which implement the pre-amplification module. Stand-alone guitar amplifiers and other sound effects all employ pre-amplifiers. As such, these products are ideal for future development.

14 Discussion

The worked described within was a learning process, where knowledge was not only gained about the technical problem and the market, but about the product development process as well. Several techniques used worked well, while others improved throughout the process and some others still could be improved upon.

14.1 Methodology

The methodology used in the technical problem definition did a good job of providing a clear background of the general operating principles of vacuum tubes and the source of non-linearity. The technical background in this paper general, however, was the product of older publications. This was largely because vacuum tube theory and development have been stagnant for half a century. Even though there have been no innovations in vacuum tube technology, there have been later innovations in terms of implementation. Information regarding these implementations could have been found through both product specifications from product user manuals and from patents and patent related publications. In hindsight, this could have created a technical background with a greater scope which encompassed both the source of the problem and the evolution of the problem over time.

14.2 Purpose and Objectives

The purpose and objectives of the product were successful in that they had clear metes and bounds and were realistic. The purpose and objectives, however, provided for the production of a module to develop a product line around. This module is designed to interact with other modules and designing these modules independently could lead to potential problems in the future. Impedance matching, operating voltages and power consumption are all issues which could affect interactions between modules. While this could eventually prove to be problematic, this in no way embodied itself in the work described. Furthermore, no foreseeable solution to deal with this without significantly increasing the scope of the project (i.e. designing future products) was theorized.

14.3 Benchmarking Market Analysis

Benchmarking and market analysis did a satisfactory job of obtaining information about large competitors, market statistics and recent trends in the market. The methodology employed, however, may have done an insufficient job of predicting future trends. Tools such as trade shows and pre-grant patent publications could have both been used as tools to predict future changes in the market. Furthermore, close monitoring of industry websites and watching for the moves of small competitors provide more means for predicting the direction of the market. The market, although stagnant, is becoming increasingly more dynamic and knowing the current state of the market is clearly not sufficient. As the market analysis was more reflective than predictive, the result was more of a statement of feasibility and general product strategy rather than a predictive product strategy. Although a predictive product strategy would have been ideal, the market still remains fairly stagnant in terms of solutions and the product strategy was largely formed based on the results of user interviews, as opposed to the market analysis.

14.4 User Needs

The backbone of the work performed was user interaction. While relationships had been forged continuously from the project's inception, the bulk of the interaction and relationship forming took place during the user needs study. The user needs study was one of the most fruitful phases of the project. In general, the methodology used was useful, particularly for the segments of professional and amateur users. The long format interview and observation provided a setting which was casual, communicative and provided for the forging of relationships. The long interview format, however, was slightly less useful with retailers, who often produced answers that were less than helpful and provided a significant amount of repeated information. Furthermore, retailers answers seemed to be biased to whatever markets their stores were serving, providing little information about the market in general. Retailers also tended to give advice about product designs, instead of providing objective answers to questions. Retailers also offered very little in terms of information regarding the buying procedures of larger stores and online retailers. This information, including what factors play into the purchasing decisions and behavior of larger retailers is critical to product sales but was not obtained.

The matrix analysis performed, while serving as a useful tool for presenting results of the user needs study, did little in terms of actually interpreting or sorting the collected data. The simple format was simply less comprehensive than the written descriptions provided. In general these written descriptions or raw interview notes were consulted in the formation of the design requirements.

The design requirements were created in accordance with the principles of axiomatic design. The creation of these requirements, however, was not as structured as described by Suh. "Domain zig-zagging" was not used in the functional breakdown; instead, user statements were merely broken down into discrete requirements and left in the functional domain. One could view the metrics as the equivalent of "design parameters" and view the mapping of these to functional requirements as "domain zig-zagging." This was not done formally, however, or intentionally to conform to the principles of axiomatic design. Furthermore, no constraints were placed on these design parameters, merely metrics for measurement. One may question the partial usage of axiomatic design. For the purpose of this project, the benefits of axiomatic design were not functional decomposition and decoupling, but rather providing a structured and traceable method for decision making. These benefits were fully reaped using a less formal functional breakdown and requirements formation process. That being said, many of the tools of axiomatic design were inevitably used in a casual manner but not documented in the formation of requirements. Although this process was not performed in a haphazard manner, much time was spent and some difficulties arose in the process of forming design requirements. The final product produced what is believed to be a comprehensive set of measurable, non-overlapping design requirements, but it is possible that stricter usage of the tools of axiomatic design would have expedited the process and removed some of the doubts that arose during the formation of design requirements.

14.5 Design

The product itself naturally lent itself to be broken down into three subsystems, the vacuum tube, the surrounding circuit and the enclosure and interfaces. In hindsight, it is perhaps clearer to think of the entire circuit and the enclosure as two decoupled subsystems, with the circuit consisting of the vacuum tube and the surrounding circuit. With the vacuum tube and the circuit coupled, a conscious decision was made to select the vacuum tube prior to the circuit type. This decision was one of the more difficult decisions to make in terms of development structure. Should one circuit type have had a significantly better performance than other circuits, it may have been suitable to select a vacuum tube that would be suitable for that circuit. Each circuit type described has its own "characteristic sound," however, and no one circuit type is known to produce a significantly more desirable sound characteristic than the others. It would be easy to point to the clear results of the selection matrices and the successful prototype as indicators that selecting the vacuum tube type before the circuit type was the right decision. We cannot compare these results to a theoretical alternative, however. Since there is no basis for comparison it is impossible to say whether this decision was better than the alternative, merely that it produced the design that it did. Such difficulties are inherent in coupled decision making. In hindsight, this was both the most subjective and easiest to question decision of the entire project.

While the order of the sub-concept selection process could be called into question, complete faith was held in the sub-concept selection processes themselves. Kesselring matrices are simple, transparent, traceable and extremely common in usage. One of the main benefits of the structured, axiomatic design approach was design objectivity and traceability, which are two of the strengths of the Kesselring matrix. The methodology to be used was almost a foregone conclusion and complete faith was placed in the results. In spite of this, there were some weaknesses of the Kesselring matrix when it came to assigning scores of subjective categories, such as aesthetic quality. Unfortunately, it is extremely difficult to come up with an objective decision making process for a subjective quality. As such, these were accounted for as best as possible.

Perhaps the only part of the sub-concept selection process that was questioned was the fact that only one final concept was selected for further development. The low cost and quick design cycles associated with circuitry make the product ideal for rapid, parallel development. Parallel development of designs generally leads to higher quality designs which better fulfill user needs. (Clark & Wheelwright, 1992) Indeed, there are many unanswered questions regarding whether unselected designs may have produced higher quality products. The project objectives called for the production of a single prototype based on the concept selection process and calling the number of designs pursued into question is in a sense calling the project objectives into question. As it stands the project ran beyond its projected timescale, however, and the pursuance of a multiple designs was a luxury not afforded by the available time and resources.

14.6 Prototyping

The prototyping process offered its own difficulties and the fact that a prototype was successfully built to specification does not mean that the process could not be improved upon. The use of a breadboard to test the circuit's functionality proved to be successful, however there were differences between the breadboard and the prototype in terms of signal path and grounding schemes. These differences required extra consideration in final prototype assembly. Part layout for assembly and to prevent electrical shorting also provided additional consideration. One initial concern in the construction of a prototype was the outsourcing of the enclosure drilling and painting. This outsourcing, however, did not lead to any problems and all parts were easily mounted to the enclosure. The lack of tight tolerances and the simple interfaces between parts facilitated this success. The final assembly of the prototype proved to provide its own difficulties and knowledge was gained regarding the product, as can be expected in any initial prototyping phase. Many wires, for example, were desoldered, recut, rerouted and rewired due to lack of product knowledge. The knowledge gained in the production of the initial prototype was clearly embodied in the prototype iteration process which was significantly more efficient.

14.7 Testing and Design Iteration

The testing of the prototype revealed information about the prototype and the process went extremely smoothly, strengthening bonds with key users and securing future sales. The results of the testing phase, however, were less ideal and embodied some of the innate difficulties of designing for the human ear. Many subjective terms were used to describe the problems with the sound quality of the prototype and how to correct these problems. There are difficulties in modifying an electrical circuit to make a signal "crunchier." It is perhaps here where the user confirmation methodology showed its weaknesses; while it is easy to tell if a user dislikes a certain sound, it is hard to modify a circuit in accordance to this statement. These difficulties are compounded by the fact that it is difficult to structure data reduction of subjective descriptions. A conscious decision was made early on in the project to use user confirmation as a measurement metric, as opposed to harmonic distortion content. While this is still believed to be a good methodology (for reasons previously stated,) this introduced some guesswork into what would be final design changes. Since user confirmation is often used as a metric for sound quality, there is a significant amount of publicly available information regarding circuit design in regards to user statements. As such, it was known that the initial's designs sound characteristic was largely dictated by its anode resistance and that lowering it would increasing the proportion of even order harmonics, creating a "crunchier" output. The amount of publicly available information was not accounted for when this metric was selected and was an unforeseen benefit of what turned out to be a commonly used quality measurement.

All in all the simplicity of the feedback, the ability to turn these into design changes and the ability of these design changes to improve product quality seemed to be more guesswork than a product of a structured system for interpreting user statements. The successful interpretation of testing results and consequential design iteration are not felt to be the product of a strong design tools, but merely the product of receiving simple feedback which aligned with publicly available information. This successful interpretation was embodied in the final prototype which showed clear improvements to the weaknesses initially identified by users in testing.

14.8 Product Development Process

The above discussion revealed several positive and negative aspects of the product development process performed in this project. These aspects are thought to be relevant not only further development of low voltage vacuum tube pre-amplifiers and products incorporating them, but in technical products whose output is to be judged by subjective human senses. There was a clear division between successful and unsuccessful tools; while objective tools such as the use of axiomatic design were successful, the use of subjective user preferences as a metric was far less successful. If one thing could have been done to improve the project, it would have been to create a stronger map between circuit parameters and their effects on the aural qualities of the circuit output. In a more general sense, while user confirmation may be an appropriate method of confirming subjective qualities, it is not useful without a clear map between user statements, design parameters and product properties. This transformation process of subjective tastes into subjective language is known to ease downstream product development processes. (Burchill & Fine, 1997) Knowing what is now known at the end of the project, the mapping of user statements to design parameters was crucial in dealing with subjective sense in a structured, objective manner and could have led to a more successful and simpler development process.

15 Concluding Remarks

The initial goal of the project was to develop a pre-amplification circuit that operates at low voltages while obviating the non-linearity associated with this operation, for the purpose of lowering device costs. A further goal was to implement the pre-amplification circuit into a distortion sound effect for guitars. The project accomplished these goals as initially set out by fulfilling the initial detailed objectives. Extensive knowledge of the problem was acquired throughout the development process about the market, user needs, the technical problem and theoretical solution which was eventually implemented.   The final design incorporated all of the knowledge gained in the process, as well as feedback from initial prototype. Several conclusions can be made from the project:

- The attenuated input common-cathode design improved linear performance of vacuum tubes operating at low anode voltages.
- The use of capacitive attenuation isolated DC voltages from attenuation while properly attenuating the input signal.
- The use of a pull-up bias resistor increased input impedance to an adequate level to prevent blocking distortion and signal reflections regardless of input frequency, while accounting for grid conduction.

- The pre-amplification module created can serve as a basis of future development and be integrated into future products.

- The distortion sound effect created sufficiently meets user needs and can be sold at a price point that is lower than that of other vacuum tube prices and competitive with solid state devices.

- Initial user reception of the prototype was positive.

- Branding was identified as a major factor in buying decisions and will be important as the product is brought to market.

- Both professional usage and user reviews were identified as key sources of information in purchasing decisions. The use of these will be a critical factor in product success.

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