Modified 5E3 Deluxe Guitar Amplifier

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ECE 445, SENIOR DESIGN PROJECT

& Physics 497 Independent Study Project

FALL 2004

With Professor Steve Errede

December 7, 2004

Project No. 29

ABSTRACT

Our project aims to solve the problems that persist in the Fender Tweed Deluxe—an old, popular guitar amplifier from the 1950s that, even until present day, remains one of the most favored sounding amps. Its major problems include too much cutoff distortion at early volume levels, uneven frequency response at mid-level tone, excessive noise, and low reliability. With design and construction considerations, we reconstructed the amplifier with the proper modifications. We then conducted voltage analysis tests in both time and frequency domains to measure distortion and voltage gains as well as a spectrum analysis to analyze the harmonic content of the output signal. These tests served as tools to compare the original Fender Tweed Deluxe with our modified amplifier to gauge the effectiveness of our improvements.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 REVIEW AND UPDATE MATERIAL

Many professional musicians continue to favor the sound of vintage Fender Tweed guitar amplifiers made in the 1950s and 1960s. Much of the reason is due to the use of tube-based circuitry rather than solid-state. Guitarists say that the distortion made by the amplifier is much “warmer” and “less harsh” than solid-state amps and the tone is more colorful and interesting.

One of the most popular amps among guitarists, especially among hobbyists who seek to recreate the old Fender tweed amps, is the Fender Tweed Deluxe (5E3). Fender does not manufacture this amp any more, but it has made the old circuit schematic for this amp public domain. People who want to buy an amp like this can either buy an original model (which would definitely require some repair and upkeep), buy a remake from a number of companies that specialize in old Fender amplifier copies, or try to build the amplifier themselves.

One problem with these amps now is that the original 12AY7 tube used in the first preamp stage is not easily available and its popular replacement -12AX7- causes the amp to distort much faster because of its higher amplification factor. In addition there have always been power dissipation concerns that have led to early power tube failure. These problems are more apparent now because the line voltage is 120-124VAC compared to 110-115VAC when the amp was originally built. These problems coupled with excessive noise and, for some people, the uneven frequency response at mid-tone are the motivation to modify the design and construction of this vintage guitar amplifier.

1.2 PROJECT OVERVIEW

Our main goal is to rectify the persisting problems in the original amplifier design. We will reconstruct the original amplifier with the necessary modifications to compensate for the original design flaws. The construction is an important aspect because the noise problem largely arose from improper construction techniques. The final test will be to compare our final modified amplifier to an original amplifier in each of the problem areas. Realistically, we cannot find exact duplicates for every part of the original amplifier. Every 12AX7 triode, 6V6 pentode, 5E3 power and output transformer will have slightly different behavioral characteristics. This is one aspect we admittedly cannot control.

1.3 SUBPROJECTS

Figure 1 shows the original Fender schematic with each of the circuit stages boxed off. Below is a brief description of the function of each stage.

Power Supply
This circuit takes in the AC line voltage, steps it up with a power transformer and uses 3 pairs of secondary tap locations to power the circuit, heat the tube filaments, and drive the rectifying tube. The rectifying tube contains a pair of vacuum diodes and the following capacitors help to rectify the signal close to DC voltage to drive the circuit. In the original amp, there was no true earth ground in the two-prong plug. The ground polarity switch (which we took out because we used a 3-pronged plug) in conjunction with the unpolarized AC 2-prong plug and .05uF/500V capacitor to the chassis provided a quasi-ground for the chassis. This was a safety hazard for musicians because of the dangerous static discharge.

Input Stage
This circuit receives the incoming guitar signal and sends the signal into the first preamp.

First/Second Preamp Stage
The filtered input signal at the grid of the triode is amplified by a factor determined by the behavioral properties of the triode and the situational bias. This amplified signal is present at the plate (anode) and is 180 degrees out of phase with the input signal.

Equalization
This is the location of the "Volume" and "Tone" knobs (potentiometers). The Volume potentiometer determines the amplitude of the signal coming from the plate of the first preamp. In effect, it controls the gain of that triode. The Tone potentiometer controls the frequency response of the signal, determining whether high frequencies or low frequencies are to be attenuated. When the potentiometer is at 0Ω, high frequencies are shunted to ground. When the pot is at 1MΩ, the high frequencies are passed through and the frequencies below the 3dB point of the filter are taken to ground.

Phase Inverter
The triode is biased such that the voltage amplification is only unity. The result is ideally a signal present at the plate with an equal magnitude as the grid voltage but out of phase by 180 degrees. The cathode of the triode will ideally be a clone of the grid signal. The output of the phase inverter is ideally two equal magnitude signals out of phase with one another by 180 degrees.

Power Stage
The power stage is composed of two pentodes and their respective bias circuitry. Each of the two out-of-phase signals coming from the phase inverter are fed into their own pentode to be further amplified. The two amplified signals are output at the pentode plates. This circuit uses a Push-Pull Class A power-tube arrangement where the current flows in each tube at all times but out of phase by 180 degrees.

Output Stage
Each of the two power stage output signals flow into a lead on the primary of the center-tapped output transformer. The transformer steps down the high voltage and steps up the low magnitude current. An 8 ohm speaker is connected to the transformer secondary to output the sound.

Original Fender 5E3 Schematic

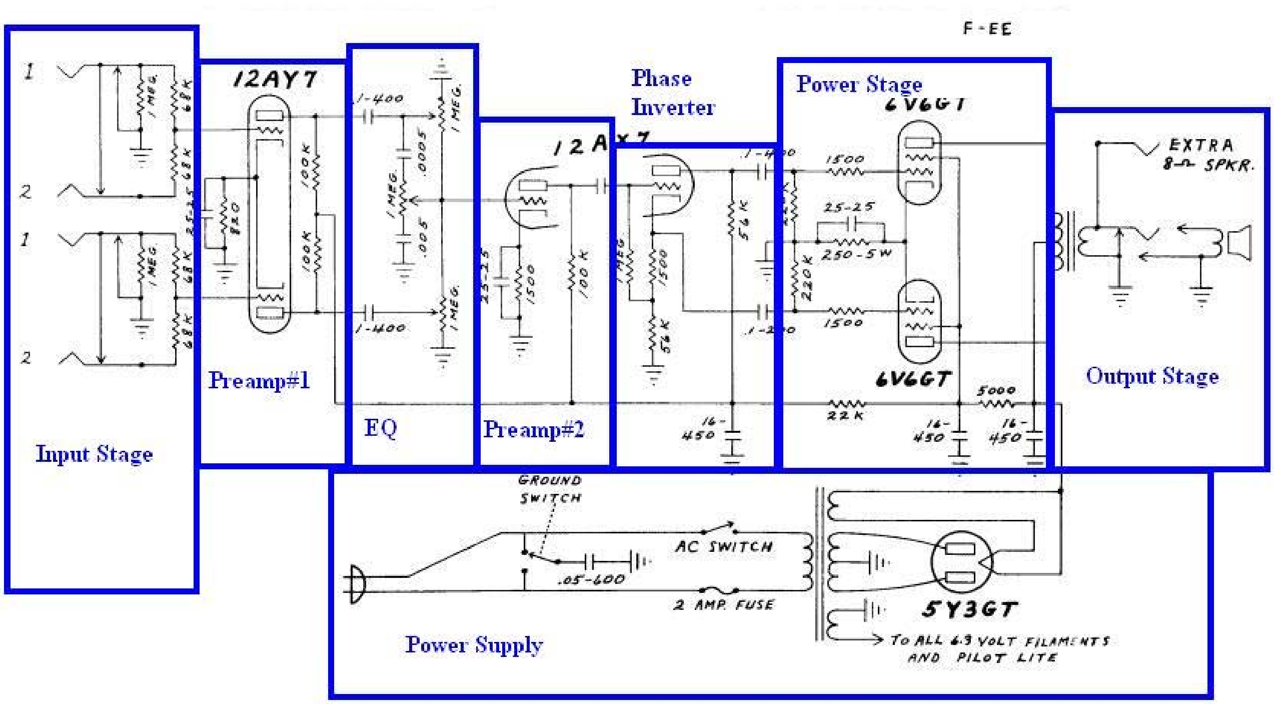

Fig. 1 Original Circuit with outlined stages

2. DESIGN PROCEDURE

Because the premise of our project is to fix and improve an existing circuit, the basic components are already designed and will not change from their original function. The problems of the original circuit will first be discussed followed by the modifications and their justifications. Figure 2.1 shows the schematic for our circuit with the red color indicating modifications.

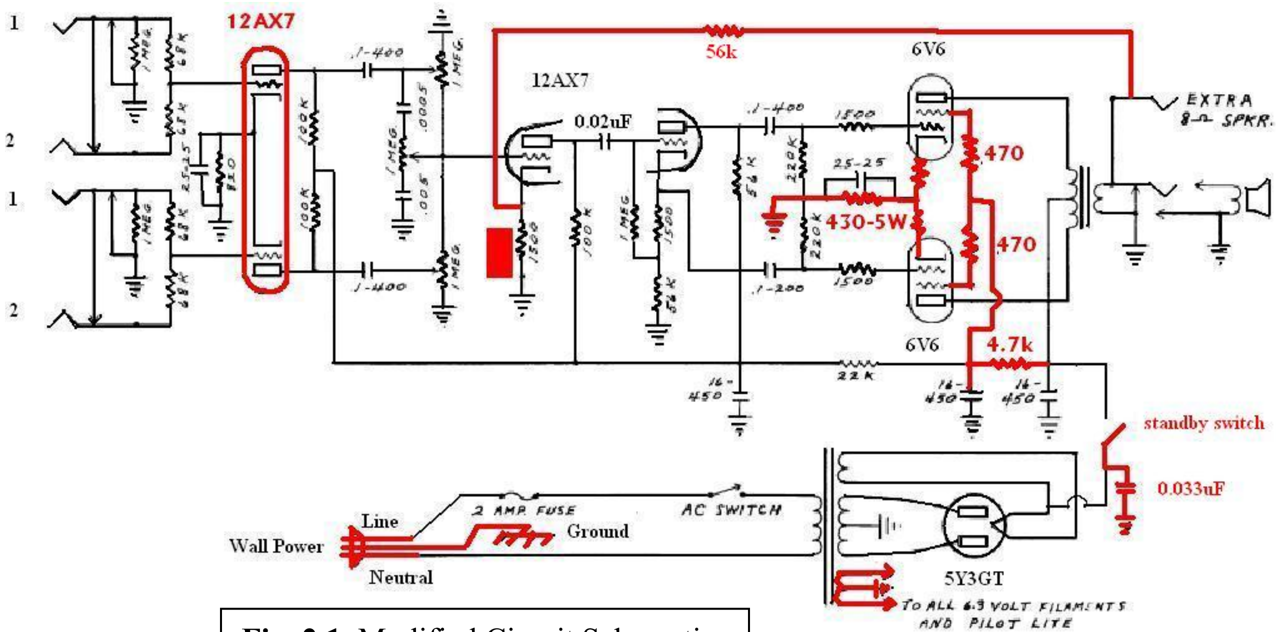

Fig. 2.1 Modified Circuit Schematic

2.1 PROBLEMS WITH THE ORIGINAL FENDER TWEED DELUXE

2.1.1 Early Cutoff Distortion

Since the 5E3 Tweed Deluxe was one of the first guitar amplifiers made, its design and construction was not flawless. One of the big problems with the amp today is that the output signal would go into cutoff distortion fairly quickly when the volume was turned up. This problem is now accentuated by the scarcity of an important original component—the 12AY7 triode of the first preamp. It has become standard for people rebuilding the 5E3 to replace to the 12AY7 with a 12AX7, which still outputs a good sound. However, the 12AX7 has a much higher amplification factor which brings the onset of distortion even sooner.

2.1.2 Uneven Frequency Response

Another problem is the uneven frequency response. When the tone potentiometer is set in the middle (note that the amp's potentiometers are audio-tapered, which means they vary their resistance logarithmically), we should ideally have a signal amplified equally at all frequencies within the human hearing range (in general about 18kHz or less). However, the original amplifier amplified the lower frequencies by almost twice as much as the higher frequencies.

2.1.3 Short Tube Life

A major gripe of 5E3 owners is how often they need to replace the tubes in the amp. The materials in the tubes wear down after long-term usage. The lack of a standby switch after the power supply stage puts stress on the tubes. The filaments of each tube were not allowed to heat up before operating the circuit. This caused more wear and tear on the tube components. In addition, the power tubes were heavily biased and their plate and screen power dissipation limits were very closely approached. This biasing problem led to early power tube failure and a need to frequently replace the power tubes. The screens of the power tubes frequently burned out because they often carried too much current. Also, the two screens were coupled, which caused unequal currents to flow against each other, and forced the screens to the same potential. Most tubes do not behave the same way, so the screens should not be at the same voltage point. When the screens pulled on each other, the power tubes did not behave correctly. These problems are enhanced by the higher B+ voltage, which is caused by a higher line voltage today than when the amp was originally designed. Therefore, even more power is dissipated in the pentodes.

2.1.4 Excessive Noise

The final deficiency of the original 5E3 Tweed Deluxe was the excessive noise and 60Hz hum caused by ground loops and harmonic interference. The original circuit utilized point-to-point wiring on a fiber board that connected to the rest of the components. Proper grounding was not implemented and long conductors connecting parts of the circuit were highly susceptible to 60Hz hum.

2.1.5 Unnecessary Changes

When some people recreate vintage amps, they use different capacitor and resistor types than originally used. Carbon composition resistors were originally used and it is important to use them when remaking a vintage amp. These resistors generate scintillating time-fluctuating "texture" to the harmonic overtones that make them sound more musical. Carbon film and metal film resistors do not have this property so they produce more plain and uninteresting tones.

2.2 DESIGN MODIFICATIONS

2.2.1 Reduced Distortion

The early cutoff at the second preamp stage is caused by too much overall amplification in the first two preamp stages. The current use of a 12AX7 amplifies the signal too much for the second amplification stage to handle. To reduce the amplification, we took the simple but effective step of removing the bypass capacitor on the cathode of the second preamp 12AX7 triode [1]. This in effect reduced the voltage amplification by a factor of 2 without affecting the frequency response within the audible range.

The RC circuit at the cathode of a vacuum triode acts as a high pass filter. The 3dB point for the 2nd stage 12AX7 preamp tube can be calculated as follows:

$$\tau_{3dB}=2\pi R_K C_K=2\pi*1.5k\Omega*25uF=0.2356s \quad (1)$$

$$f_{3dB}=1/\tau_{3dB}=4.244\text{ Hz} \quad (2)$$

The audible range we are usually concerned with is 82.41 Hz (low E on a guitar) up to about 16-20kHz (average upper boundary of human hearing). So, the step up in the gain response caused by the filter will not affect the audible frequency range. For the concerned range, the gain will be at maximum.

With the capacitor in parallel with the cathode resistor, it was able to shunt most of the AC voltage to ground because of its low reactance. Nearly all frequencies above the determined 3dB point above are shunted to ground. The capacitor had a reactance of :

$$X_c=1/2\pi fC=1/2\pi f(25uF)=6366.2/f \tag{3}$$

For frequencies above the 3dB point, the capacitor begins to act more like a short circuit since the reactance becomes low [2]. This would reduce the voltage ripple at the cathode and make the grid-to-cathode voltage more negative. The larger negative differential biases the tube more and outputs a lower current and higher voltage at the plate. Even though the voltage gain increases, the available voltage headroom does not, which leads to the plate voltage to clip at higher voltages. Removing the cathode bypass capacitor allows the voltage at the cathode of the 2^{nd} preamp gain stage to swing in conjunction with the voltage at its grid. This is a form of local negative feedback and thus it reduces the gain and allows more variation in the volume control before cutoff distortion occurs.

2.2.2 Improved Frequency Response

The frequency response of the original amplifier can be controlled with a "Tone" potentiometer. When the potentiometer is dialed to "0" or zero resistance, the high frequencies are shunted to ground and the filter attenuates the high frequencies for a bass sound. When the potentiometer is moved toward the maximum of "12" or the maximum resistance of 1MΩ, the filter attenuates the low frequencies for a more treble sound. When the potentiometer is in the direct center, the frequency response should ideally be flat; an evenly amplified representation of the output of the first preamp.

As shown in Figure 2.3, the response is not flat. When we took actual measurements on the original 5E3, the response was similar. High frequencies were attenuated almost twice as much as low frequencies were. It is interesting that the Tone control is *upstream* of and *not enclosed* by the feedback loop. A feedback loop seemed to be a reasonable solution. Since the output of the amplifier should be simply an amplified version of the signal through the circuit, sending negative feedback should reduce the low frequencies more than the high frequencies [3]. We modeled our feedback loop after the one used on the Fender 6G2 Princeton amplifier, the circuitry of which is essentially very similar to that of a single channel 5E3 Deluxe, with a feedback loop. This consisted of a 56kΩ resistor connecting the feedback from the secondary of the output transformer to the cathode of the second preamp triode. Since the feedback loop will be reducing the gain at high frequencies more than at low frequencies, the overall gain will be reduced.

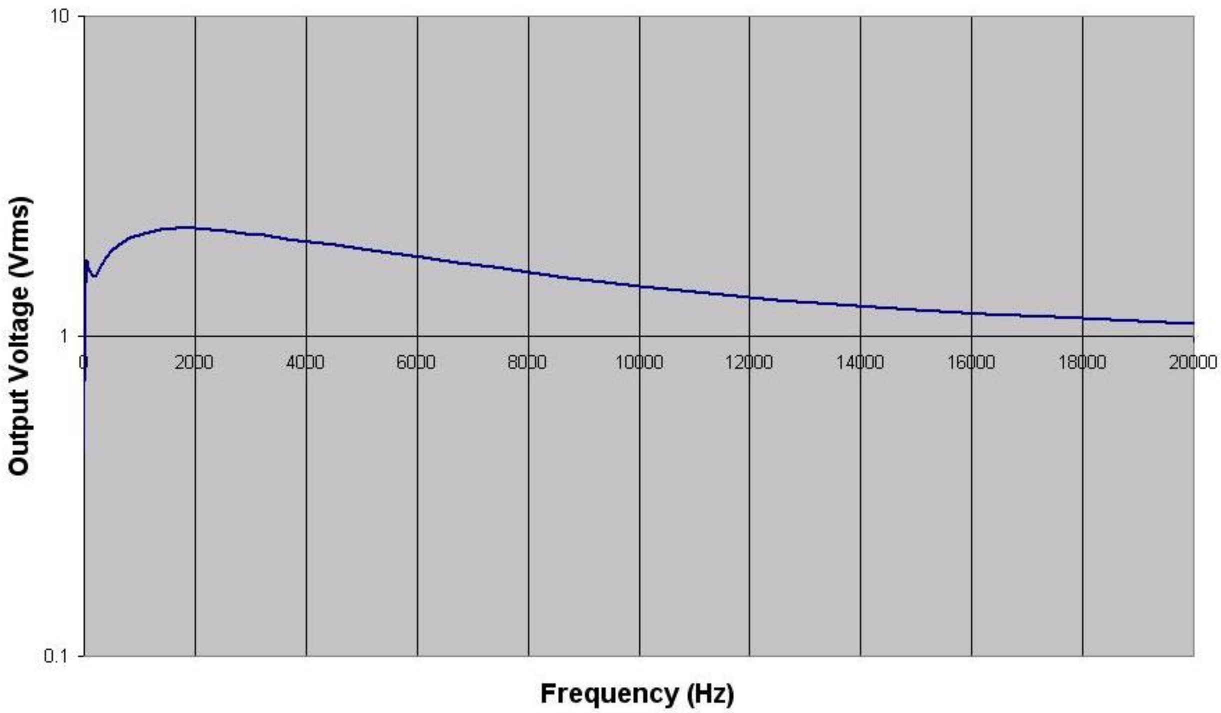

Fig. 2.2 Frequency Response of Original circuit

2.2.3 Improved Tube Durability

In the original 5E3 circuit, the filaments and cathodes would not heat up instantaneously so the circuit would force the tubes to function before the electron cloud fully gathered around the cathode. The cathode is the most important element because thermionic electrons are emitted from it. This had the potential to damage the tubes over time with cathode stripping. A simple protection of the circuit was to insert a standby switch after the power supply circuit. This would allow the filaments and cathodes of the tubes to heat up properly until ready for operation. In addition we attached a capacitor to the upstream side of the standby switch, which shunted all of the transient voltage and high frequency interference to ground and also provided a small load to the power supply so we could measure the B+ voltage at standby. We used a 0.033uF capacitor, which gives a reactance of $c=1/2\pi fC=1/2\pi f(0.033uF) =4.8*10^6/f$. This ensures that most frequencies will be passed through. Very high frequency signals, such as TV signals, will add noise to our signal. These are filtered out by this capacitor, which has much less ESR (Equivalent Series Resistance) than electrolytic capacitors at high frequencies.

The original power circuit drove the 6V6 pentodes at currents around 45 mA each (for V_{ACline} = 125 V_{ACrms}. This is the current from the cathode and is approximately equal to the current through the plate. Since the plate to cathode voltage is about 300V, the power dissipation in the tubes is (300V)(0.045A)=13.5 W. This is dangerously close to the 14W DC power rating of the tubes, which leads to shortened tube life. We resolved to bias the power tubes at a lower current by empirically raising the value of the cathode resistor from 250 to our final value of 430Ω. This produced a cathode current of 28mA. Because of a pentode's characteristics, changing the resistor value did not change the plate voltage very much. Taking the plate voltage to be practically unchanged, the DC power dissipation in the power tubes in our circuit was only (300V)*(0.028A)=8.4W. This power dissipation is at a much safer distance from its power limit.

We also deliberately wanted to change the 250Ω/5W 6V6 cathode resistor (which originally saw a line voltage of 110-115Vac, not 125Vac) to 430Ω to take it out of deep ClassA, which makes the amp sound extremely compressed ("constipated") at all volume levels – lacking any dynamic/touch-sensitive response and lacking sustain and "singing quality" in the amp. Biasing the 6V6s more conservatively at around 28mA with the choice of 430Ω/5W cathode resistor gives the amp much more headroom, much greater dynamic/touch sensitive response, and results in the amp having much greater sustain and singing quality at stage volume. This is because the amp now has greater compression headroom as well.

The screen of the pentode can also draw significant amounts of current. Because of this, the screen has its own power rating. In addition to the power rating of the tube being dangerously violated, the screen also has a history of too much power dissipation. To account for this, a divider circuit of 2 resistors decouples the two screens of the pentodes. We used industry standard 420 Ω resistors normally used to decouple the screens of the power tubes.

Another advantage of decoupling the 6V6 screens is that allows each 6V6 screen to operate at its own potential. The circuit ideally has the same input signal entering the two power tubes but out of phase by 180 degrees. The circuit should also ideally have two power tubes with the same characteristics, meaning we have a matched pair. This is almost never the case. As a result, the two 6V6 screens fight to force the other at their own voltage, putting detrimental stress on the 6V6 pentode. Decoupling the 6V6 screens with the pair of resistors allows each screen to operate at its own voltage potential and allows its own current to flow. The screen resistors also serve as a protection device for the power tubes. Originally the coupled screens were connected directly to a 16uF rectifying capacitor. If one of the screens shorts out, the capacitor very rapidly dumps its stored energy of $(1/2)CV^2$ into the power tube, which most likely will overheat and destroy the tube. The resistors are now a buffer for the screen should such an event occur. The time constant $\tau_{scr} = 2\pi R_{scr}C_{scr}$ slows the rate of discharge and helps to keep the dissipated screen power less than 2W. In this case the time constant is equal to 2π*470*16uF = 0.047s. The power will now be dumped on the resistors instead of the power tubes. This means losing a cheap resistor as opposed to a much more expensive power tube.

2.2.4 Noise Reduction

The final modifications made involved the construction of the circuit. The original builders of the Fender 5E3 Deluxe did not implement proper grounding techniques or pay undue attention to the interference of 60Hz hum introduced by the power supply and interfering harmonics introduced by the environment. They did not realize that the low voltage levels of the input and equalization stages were very sensitive to interference and needed to be protected before the noise was amplified in later gain stages.

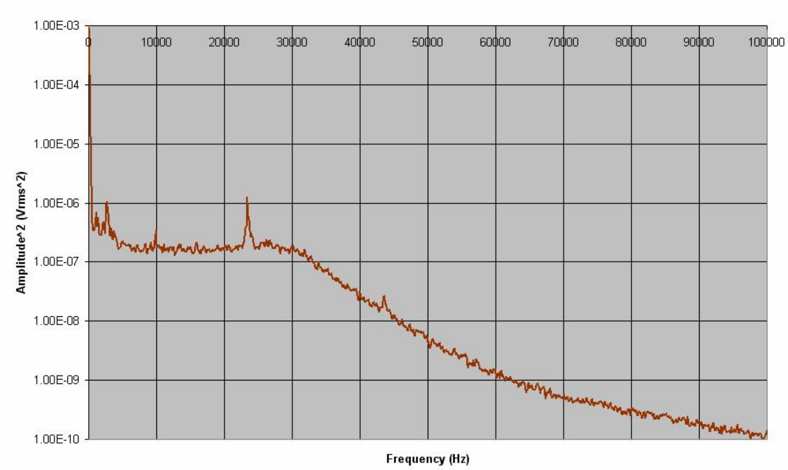

Fig. 2.3 Noise Floor of Original Amp

Figure 2.3 shows the original amplifier's Noise Floor, which is the amount of noise present at the speaker without applying an input to the speaker. This means that whatever voltage is appearing is due to the noise in the circuit alone. The spikes present are at 3.5kHz, 24kHz, and 44kHz are most likely due to the ambient noise in the room where the measurements were made – from PCs, LAN/Ethernet, and other electronic devices. This is represented by the Fourier Transform on a 1-100,000Hz scale.

The first noise problem we fixed was eliminating the various ground loops that appeared in the original circuit. Early guitar amp builders often used the chassis as the ground. This caused a lot of problems. Sometimes there could be inconsistencies in the chassis metal and the entire piece was not at one fixed potential. This caused small currents to flow in the chassis itself between the different ground points. Even if the chassis was at one potential, the currents would still flow together and create ground loops. The currents would cross paths and create interference that usually carried back to the input. This interference, although small at the input stage, would later be amplified along with the signal to have a significant impact. The fundamental operative for proper grounding (i.e. no ground loops) is returning all currents as directly as possible to their respective power source, no matter how small – e.g. a guitar pickup is a power source of a few hundred picowatts. If this is done properly, then wires attached to star ground simply maintain earth potential on the distributed star ground "network" – only very tiny transient currents flow in doing this. We used a method called distributed star grounding. We used a bent metal washer sandwiched between the power transformer and the chassis as the primary star ground point (seen at the bottom of Figure 2.4; the bundle of aqua-green ground wires lead into the star ground). This would serve as the physical grounding point, so all of the original circuit grounds would lead here instead of directly into the chassis. Since the washer was in contact with the chassis, it was at nearly the same potential. This method directed all of the currents to ground into a communal point, which eliminated different paths to ground crossing each other and creating interference.

Fig. 2.4 Inner detail of circuit –star ground and filament conductors

Another consideration for ground loops was raising the Switchcraft Fender-style input jacks off of the chassis with plastic washers to prevent them to be directly grounded to the chassis. In addition, small-toothed star washers were also added to hold the jacks in place when accounting for vibrations in the amplifier. The input jacks on the original 5E3 Deluxe were originally grounded to the chassis since they were flush against it and this created a ground loop path. The idea that a signal needs to be returned to its source indicates where a ground should be connected. The guitar signal flowing through the 1MΩ resistor across the input jack needs to be returned to the guitar through the signal ground (guitar cable). So the ground-end of the resistor is soldered to the ground point of the input jack. To prevent potential differences in ground potentials, the input jack ground is daisy-chained back to the star ground along with the rest of the circuit, but is first tied to the 1st stage preamp cathode ground point. The same technique is also utilized with the potentiometers. In addition, the earth ground wire of the AC line power is also star grounded with the center taps used on the power supply secondary. The star ground isolates the ground to a point to avoid interfering current paths. The earth ground on the AC power cord is approximately 2 inches away from the main star ground point. This is deliberate to decouple the two grounds at very high frequencies (e.g. f >10MHz) in preventing interference. Therefore, any noise that is carried through the signal path is not coupled in the transformer. Likewise any noise carried in from the wall socket will not be distributed throughout the circuit. The purpose of earth ground is simply to keep the amp chassis at earth ground potential. We don't want it to do anything else – whatever else is happening, it is not something earth ground is supposed to deal with.

In addition to ground loops, 60Hz hum and high frequency interference added harmonic interference with the low-level input signal (at a low voltage), which would later be amplified. To prevent the 60Hz hum in the filaments from the power supply, O'Connor suggested a center tapped 6.3VAC configuration and the filament wires from the secondary were tightly twisted together to cancel currents (this can be seen in Figure 2.4; the black and white wires are the filament conductors) [4]. The center tapping ensured equal magnitude, but opposite phase, signals traveling on each lead from the secondary. Since the two leads are out of phase, when they are twisted, any 60Hz interference is about equal on both conductor and will destructively interfere with one another. This eliminates the 60Hz hum in that stage. The 6.3 VAC "lead dress" is such that it is well away from all signal path components and 90˚ to signal wires. This minimizes the capacitive and inductive coupling/pickup from the heater wire pair to the signal wires. In addition, signal path wires should hug or be in proximity to the chassis, which is at earth ground. The chassis then helps to shield the signal wires from external noise, which is most critical in the early preamp stages (because the noise gets amplified over and over in subsequent gain stages).

The sensitive input and equalization stages are highly susceptible to high frequency interference from surrounding elements such as computer signals, RF, and television signals. To prevent this interference from affecting the circuit, we used high-quality, shielded coaxial cables in the input and equalization stages, which connect into the input jacks and the potentiometers. The twisted shield around the coax, as shown in Figure 3.5, screens out the interfering signals. By grounding the shield, the shield shunts the interference to ground, further eliminating noise in the circuit. An important consideration is to only ground one end of the shield at the signal production (generation) end of the coax cable. If both ends of the shielding are grounding, a path is created through the chassis to each ground, which is an undesirable ground loop. Grounding one end suffices to pull the shield to signal ground.

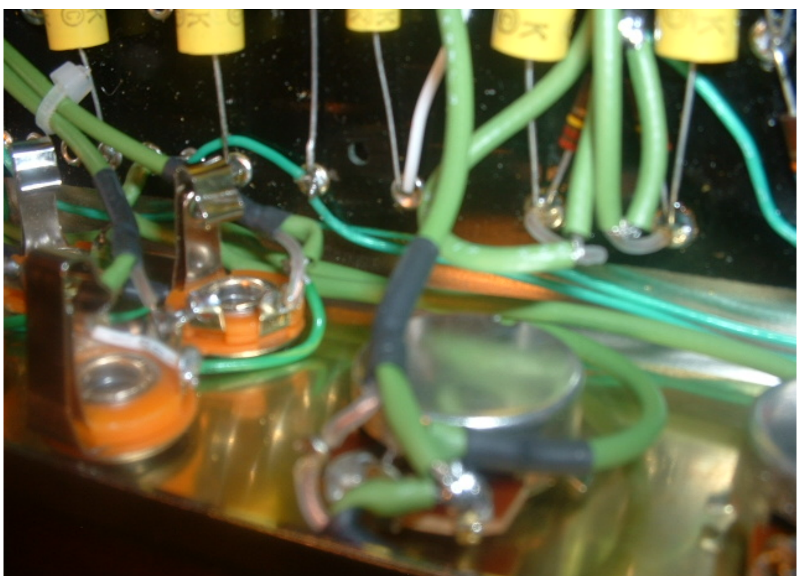

Fig. 2.5 Inner detail of shielded coax cables attached to the potentiometer and input jacks

3. DESIGN VERIFICATION

3.1 TIME DOMAIN TESTS

The original Fender 5E3 tweed deluxe sounded great a low volume levels but, with a 12AX7 installed as the 1st stage preamp tube, it quickly became distorted after the volume level reached a value of 2. In order to demonstrate the distortion of the input signal, the output voltage waveform at the speaker terminals was plotted with a 100 mV, 100 kHz input (described later in Fig. 3.1.2). The input signal was generated with a function generator, and input to the speaker's bright 1 channel. The output was taken at across an 8 ohm, 25 Watt non-inductive load resistor (dummy load of pure resistance) at the secondary of the output transformer that simulated the speaker's impedance. The signal was not connected directly to the speaker because single frequency signals at high volume levels produce discomforting sounds and we were working in a lab with other people. The output voltage waveform to the oscilloscope from the speaker terminal was connected with a 10 M-Ohm resistor to protect the oscilloscope from high voltages. This is reflected in the output waveforms as a reduction of 10 in the voltage amplitude. ***Note: Vout and output voltage in the following graphs indicate the voltage taken at the 8ohm load attached to the output transformer secondary. Modified 5E3 indicates the addition of the feedback loop and removal of the 1st stage preamp bypass capacitor. Original 5E3 indicates the exclusion of these changes. All tests were done on the same amplifier with the exception of the Floor Noise comparison where we compared our amplifier to a real original '58 Fender 5E3 owned by Professor Errede.***

3.1.1 Output at Various Volume Levels

The first test we conducted compared the signal output of the original 5E3 Deluxe design (with 1st preamp stage 12AX7) at various volume levels using a 10 mV input signal (Fig. 3.2.1). We used a 10 mV, 1 KHz input signal because the small signal does not allow the amp to go into cutoff and we can isolate the effect of the volume undistorted. The test was conducted to provide a benchmark for comparison since the output signal is undistorted.

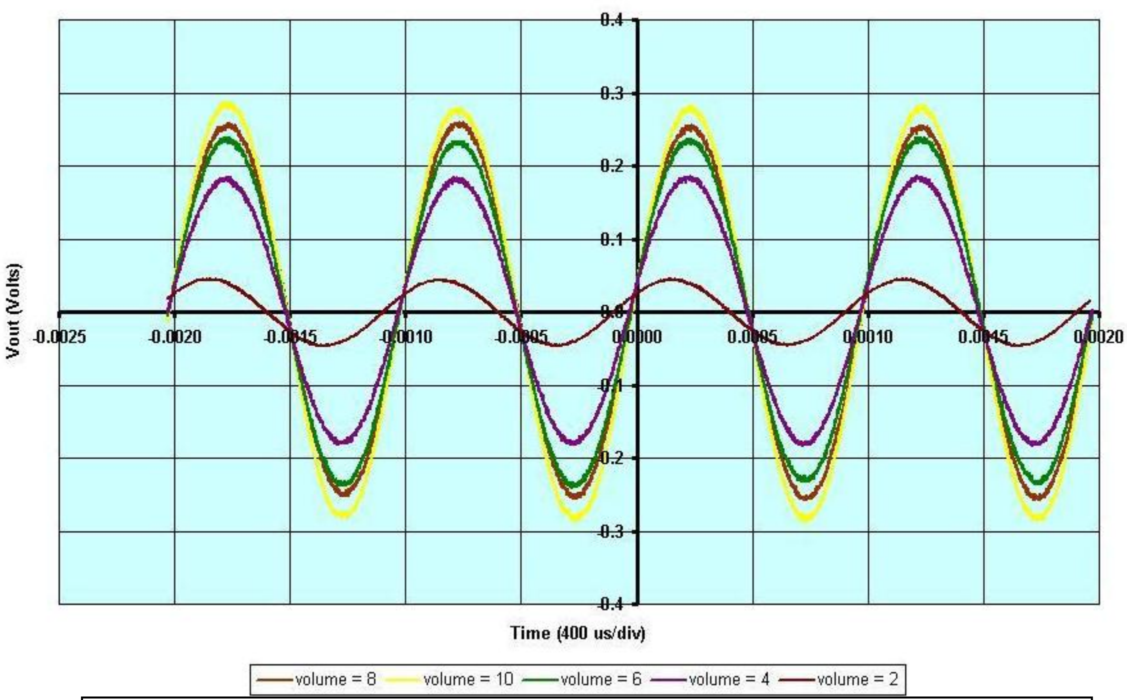

Fig. 3.1.1 Output voltage on original 5E3 design with varied volume levels using a 10mV, 100kHz sinusoidal input

3.1.2 Output voltage waveform of original design

The original design of the Fender Tweed 5E3 Deluxe (with 1st preamp stage 12AX7) began to produce a distorted sound shortly after turning the volume knob past a level of 2. This effect could be easily heard by a discerning listener, but we wanted to quantify the effect of volume level on distortion. Therefore, we input a 100 mV, 1kHz signal into the amplifier and varied the volume level, plotting the output waveforms of the speaker terminal. Figure 3.1.2 suggests that the original design goes into cutoff distortion at a volume level of 2.

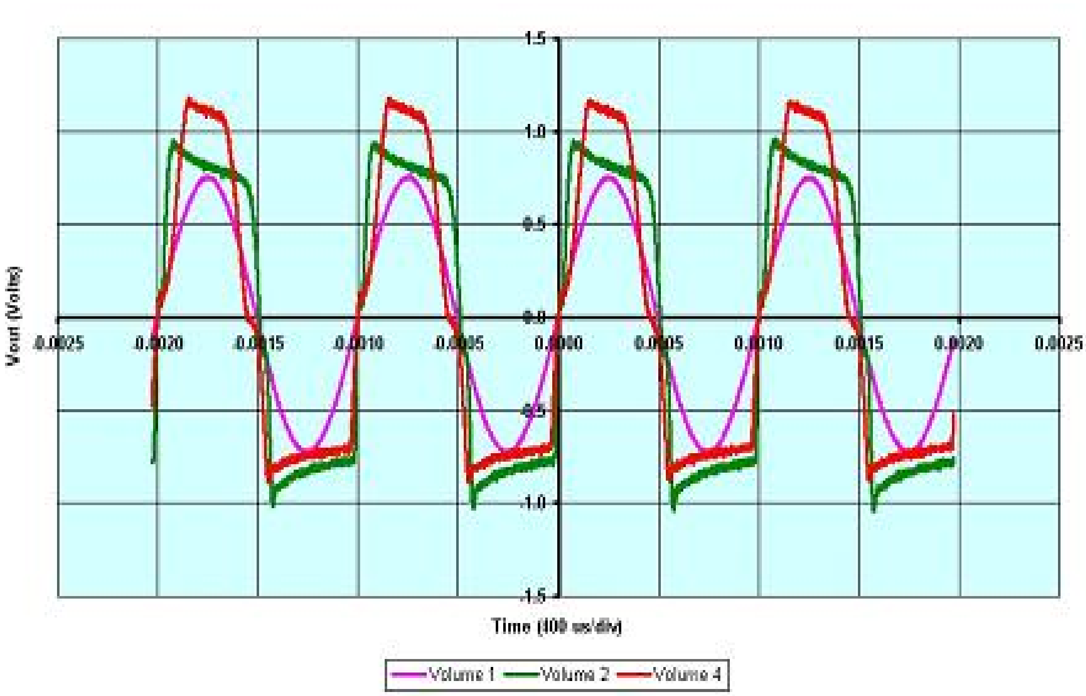

Fig. 3.1.2 Output voltage on original 5E3 design with varied volume levels using 100mV, 1kHz input sine wave

3.1.3 Output voltage waveform with cathode capacitor taken out

A major consideration in modifying the original design was to improve the input signal's integrity at higher volumes. We wanted to drive the amplifier at higher volume levels without driving the signal into cutoff distortion. By removing the cathode bypass capacitor at the second pre-amplification stage, we allowed the cathode voltage to vary directly with the signals input and thus dynamically adjust its bias point accordingly. This produced a more accurate amplification of the signal but reduced the signal's amplification by a factor of 2. Figure 3.2.3 shows the effect on distortion of removing the 2nd stage cathode bypass capacitor. After removing this capacitor, we were able to increase the volume level to a value of 4.7 before the onset of cutoff distortion.

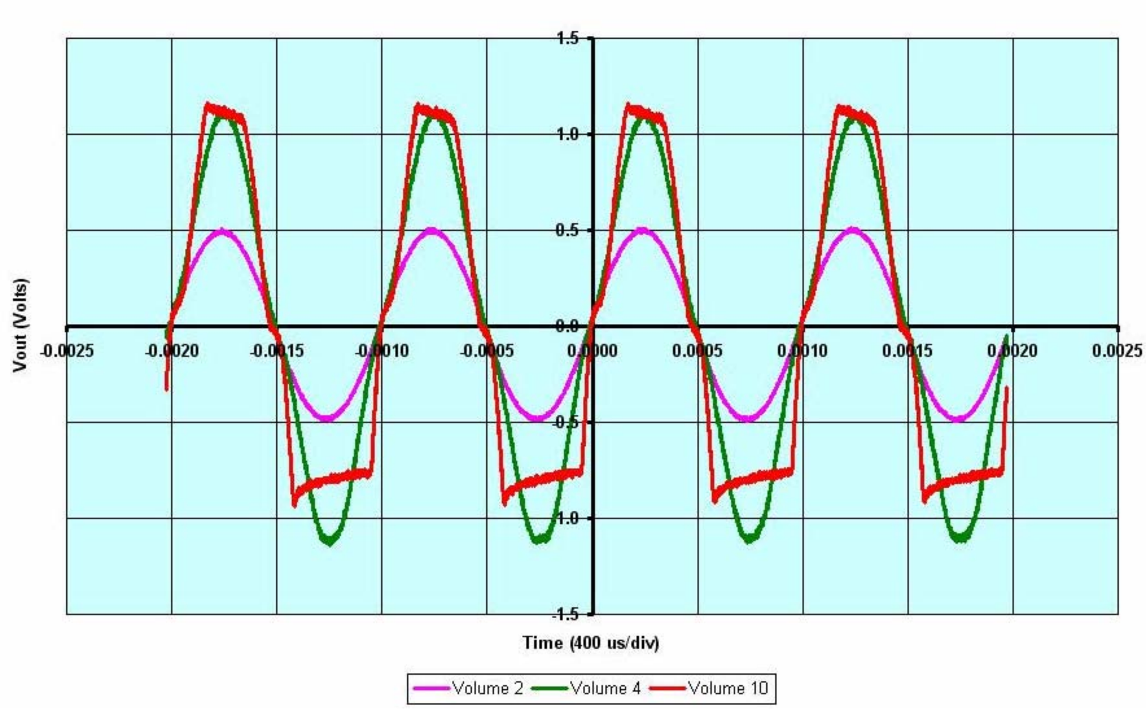

Fig. 3.1.3 5E3 design with 2^{nd} stage cathode bypass capacitor removed; Volume levels varied with 100mV, 10kHz sine wave input

3.1.4 Output voltage waveform with addition of feedback loop

Removing the 2^{nd} stage cathode bypass capacitor improved the ability to drive the amplifier at higher volume levels before the onset of distortion. But we wanted to drive the amplifier even more and maintain the signal's integrity. The addition of the feedback loop helped to accomplish this. We added a 56kΩ resistor from the output transformer secondary to the cathode of the second pre-amp triode. After the addition of the feedback loop, we were able to increase the volume level to a value of 7 before the onset of cut-off distortion (Fig. 3.1.4). Note, also, that the addition of a feedback loop, while reducing distortion levels at the output of theamp, also reduces the overall gain of the amp, as can be seen by comparing the volume 4 settings (for example) in Fig. 3.1.3 vs. Fig. 3.1.4.

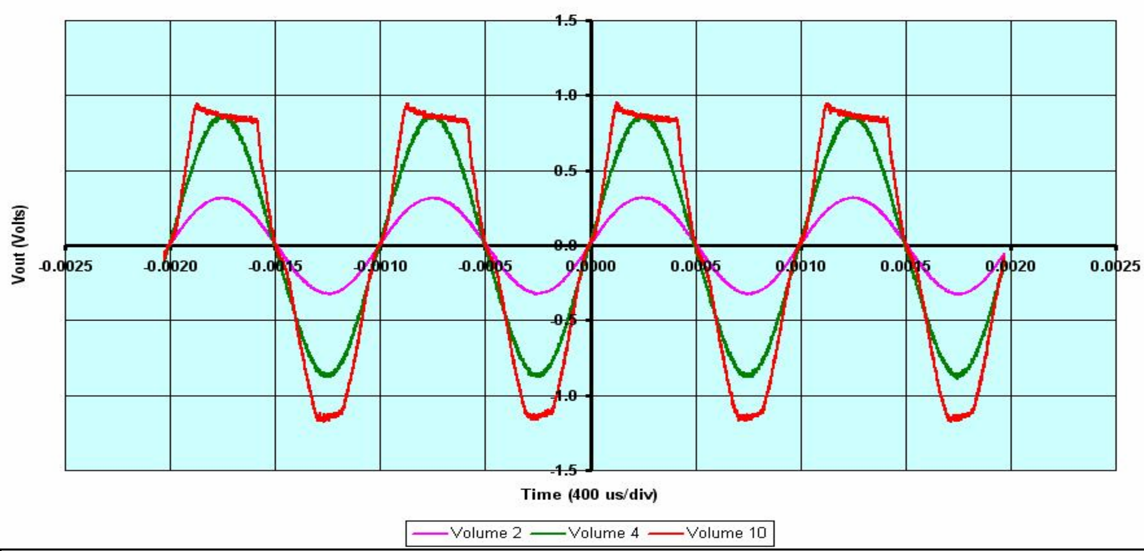

Fig. 3.1.4 Modified 5E3 circuit (no 2^{nd} stage cathode bypass capacitor; addition of feedback loop); Volume levels varied with 100mV, 10kHz sinusoidal input

3.2 FREQUENCY DOMAIN TESTS

The original Fender Tweed 5E3 Deluxe with 12AX7 1st preamp tube introduced higher order harmonics into the input signals at low volume levels. The voltage waveforms from section 3.1 demonstrate this as cutoff distortion and the frequency spectrum verifies this result as the addition of high amplitude higher harmonics.

3.2.1 Output frequency spectrum at various volume levels

The first test we conducted compared the frequency components of the original design's signal output at various volume levels (Fig. 3.2.1). A 10 mV, 1 kHz signal was input into the amplifiers bright 1 channel and the output from the speaker terminal (with an 8Ω/25W non-inductive dummy load) was input to a HP3562A dynamic signal analyser. Again, we used a 10 mV 1kHz input signal because the small signal did not allow the amp to go into cutoff and we can isolate the effect of the volume undistorted. This test provides a baseline case for comparison since the output signal was undistorted. The graph shows that the amplifier introduces low amplitude higher order harmonics into the input signal at all volume levels, and these harmonics increase in amplitude as the volume level increases. Note also the 60Hz and 60Hz harmonics apparent below which have their own respective peaks, though not as high as the amplifier's fundamental frequency and its own harmonics.

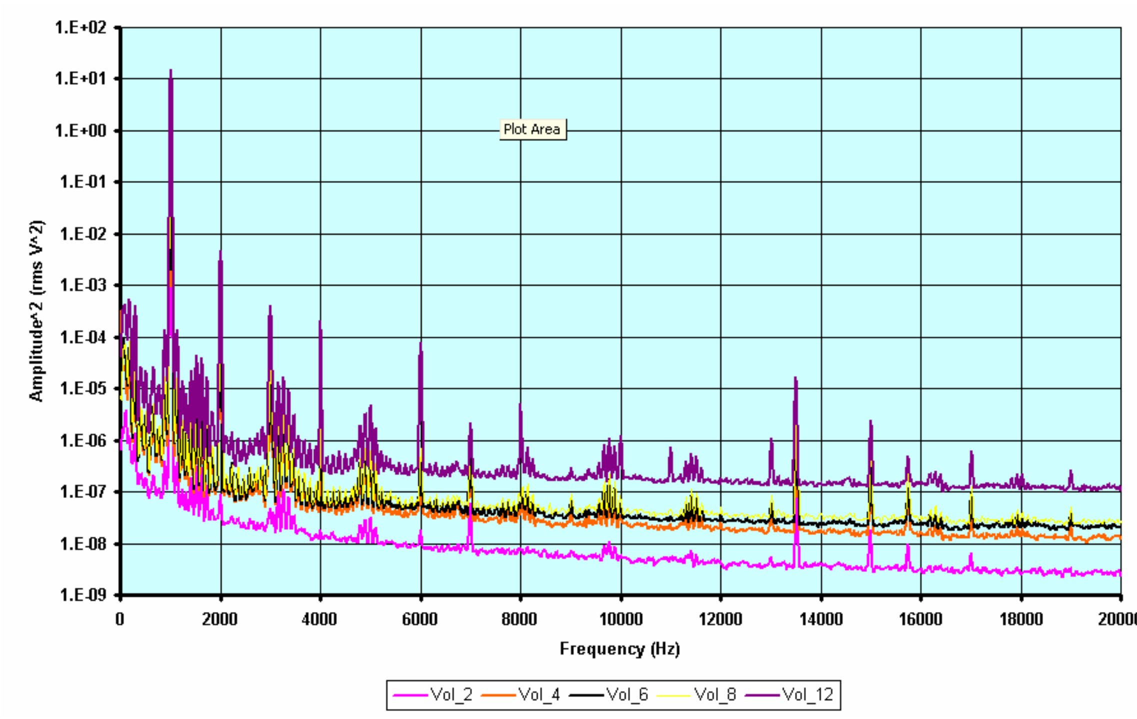

Fig. 3.2.1 Effect of volume level on frequency spectrum. 10mV 1kHz input sine wave Original 5E3 Deluxe with 12AX7 1st stage preamp tube

3.2.2 Output frequency spectrum of original 5E3 Deluxe design

A 100 mV, 1 kHz signal was input to the amplifier's bright 1 channel and the output from the speaker terminal (with 8Ω/25W non-inductive dummy load) was input to the HP3562A dynamic signal analyzer. Figure 3.2.2 demonstrates the addition of higher order harmonics and overtones at low volume levels. The input voltage of this test was 10 times higher than that of 3.2.1 and the resulting graph shows that the higher order harmonics have much higher amplitudes due to the signal going into cutoff distortion. At a volume level of 2, the amplitudes of the higher order harmonics were relatively low but they increased substantially as the volume increased to a value of 4.

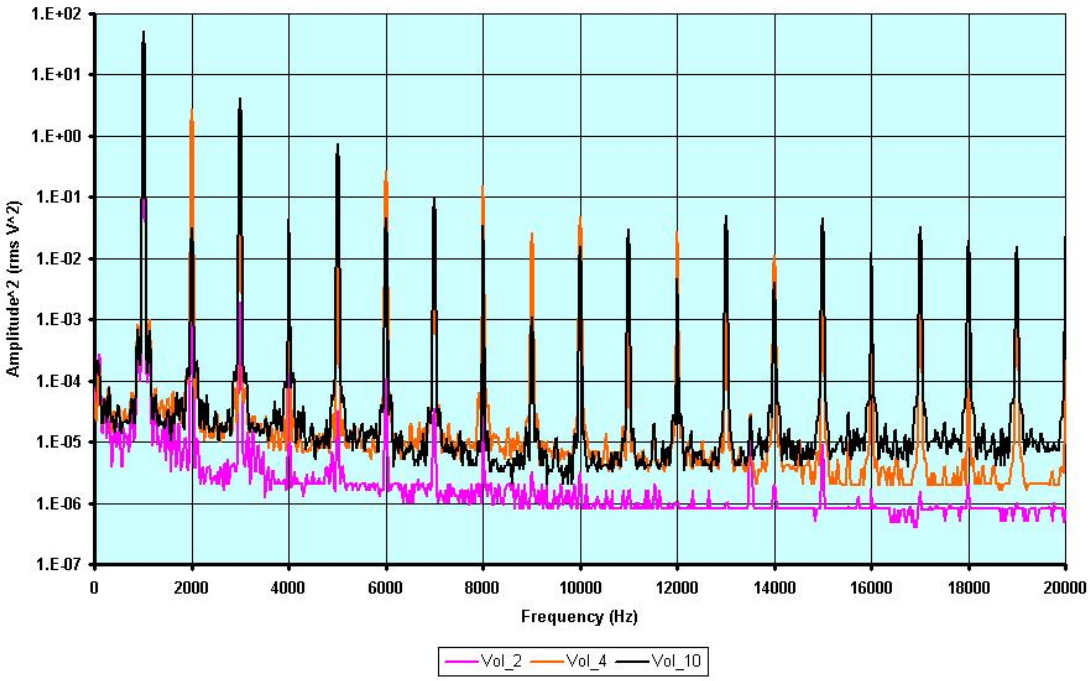

Fig. 3.2.2 Frequency spectrum at 8Ω dummy load of original 5E3 Deluxe circuit (with 1st stage 12AX7 preamp tube) at different volume levels. 100mV 1kHz sine wave input

3.2.3 Output frequency spectrum with cathode capacitor taken out

The removal of the cathode capacitor on the second pre-amp stage triode improved the ability to drive the amp at higher volume levels while maintaining the signal's integrity. This was shown in section 3.1.3 with more accurate output signals at the speaker terminal at higher volumes. Figure 3.2.3 further demonstrates this result. The amplitude of the higher order harmonics introduced into the input signal has a smaller amplitude at high volume levels than when compared to the higher order harmonics from the original schematic seen in Figure 3.2.2.

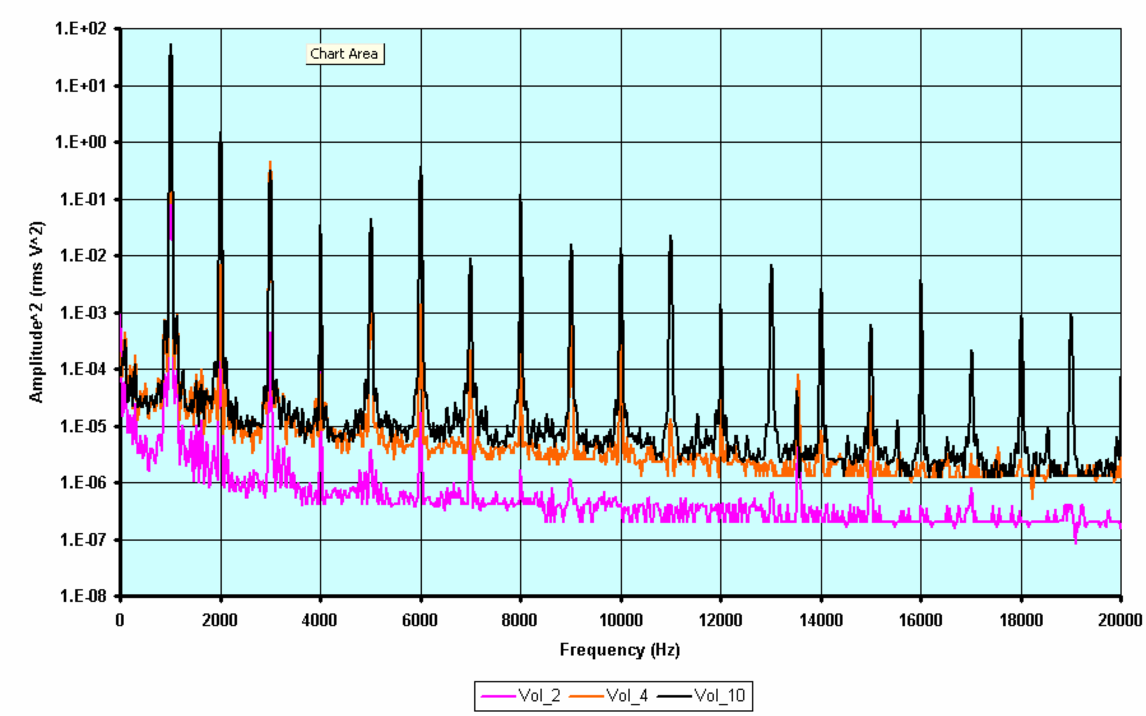

Fig. 3.2.3 Frequency spectrum at 8Ω dummy load of 5E3 Deluxe circuit (with 12AX7 1st stage preamp) without 2nd stage cathode bypass capacitor at various volume levels. 100mV 1kHz sine wave input.

3.2.4 Output frequency spectrum with addition of feedback loop with 56kΩ resistor

The addition of the feedback loop to the previously modified 5E3 Deluxe circuit increased the value the volume level could reach before going into cutoff saturation to a value 7. The resulting output signal therefore was smoother at higher volume levels and this is reflected in its frequency spectrum as a decrease in amplitude of the higher harmonics. Figure 3.2.4 verifies this result. It shows that even at volume level of 10, the higher order harmonics have considerably lower amplitudes.

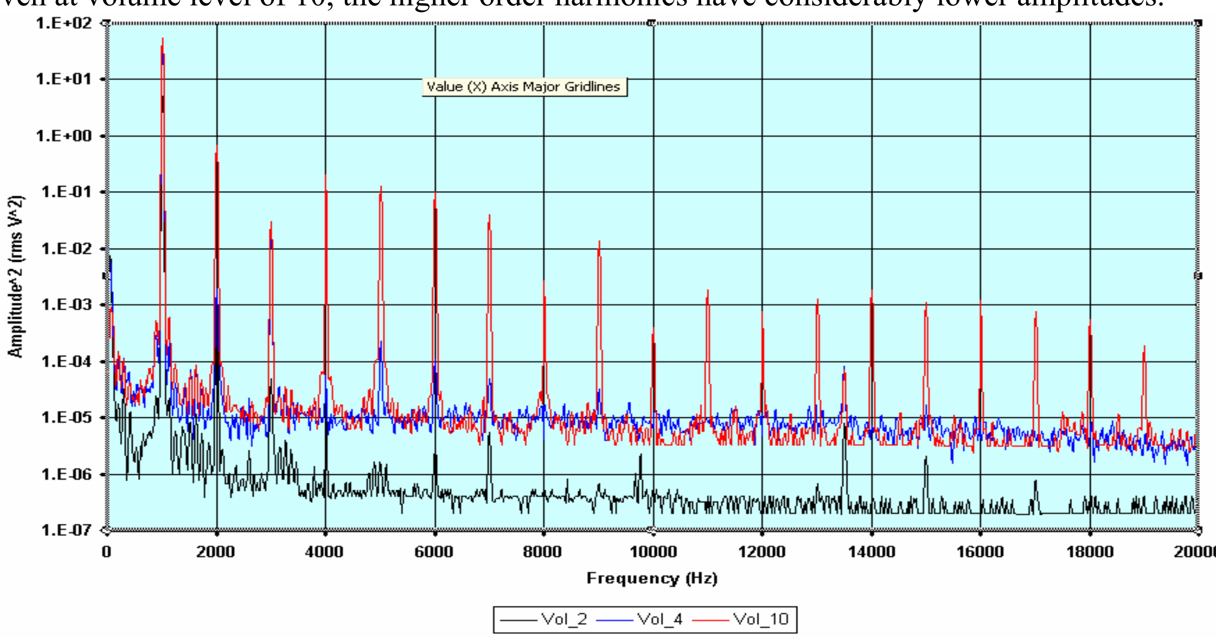

Fig. 3.2.4 Frequency spectrum of modified 5E3 Deluxe (with 12AX7 1st stage preamp) circuit with feedback at various volume levels. No 2nd stage cathode bypass capacitor

3.3 NOISE FLOOR MEASUREMENTS

The original 5E3 Deluxe with 12AX7 1st stage preamp design produced noticeably loud 60 Hz hum due to poor grounding and wiring techniques. The dynamic signal analyzer helps to quantify the reduction in hum due to improved fabrication techniques. These changes included using coax cable and grounding the shield to conduct high frequency interference signals to ground. The use of plastic washers isolating at the input jacks prevents grounding of the input signal at the chassis. The use of distributive star grounding techniques helped to prevent ground loops. Tightly twisting the filament heater wires and care in their lead dress also reduced 60Hz pickup. The following tests helped to measure the effectiveness of our fabrication techniques.

3.3.1 Floor noise level with amplifier off

The noise floor level measures the frequency components of the signal at the amplifier's speaker terminal using 8Ω/25W non-inductive dummy load with the absence of an input signal. The first test was conducted with the amplifier turned off (Fig. 3.3.1). The signal at the output of the dummy load speaker terminal was input to the HP3562A dynamic signal analyzer. The resulting graph shows the frequency components of the signals in the amplifier due to external interference patterns and waves and general noise created by the circuit. This test functions as a baseline case for comparison since the resulting signal is only a measure of the interaction between the amplifier and the environment.

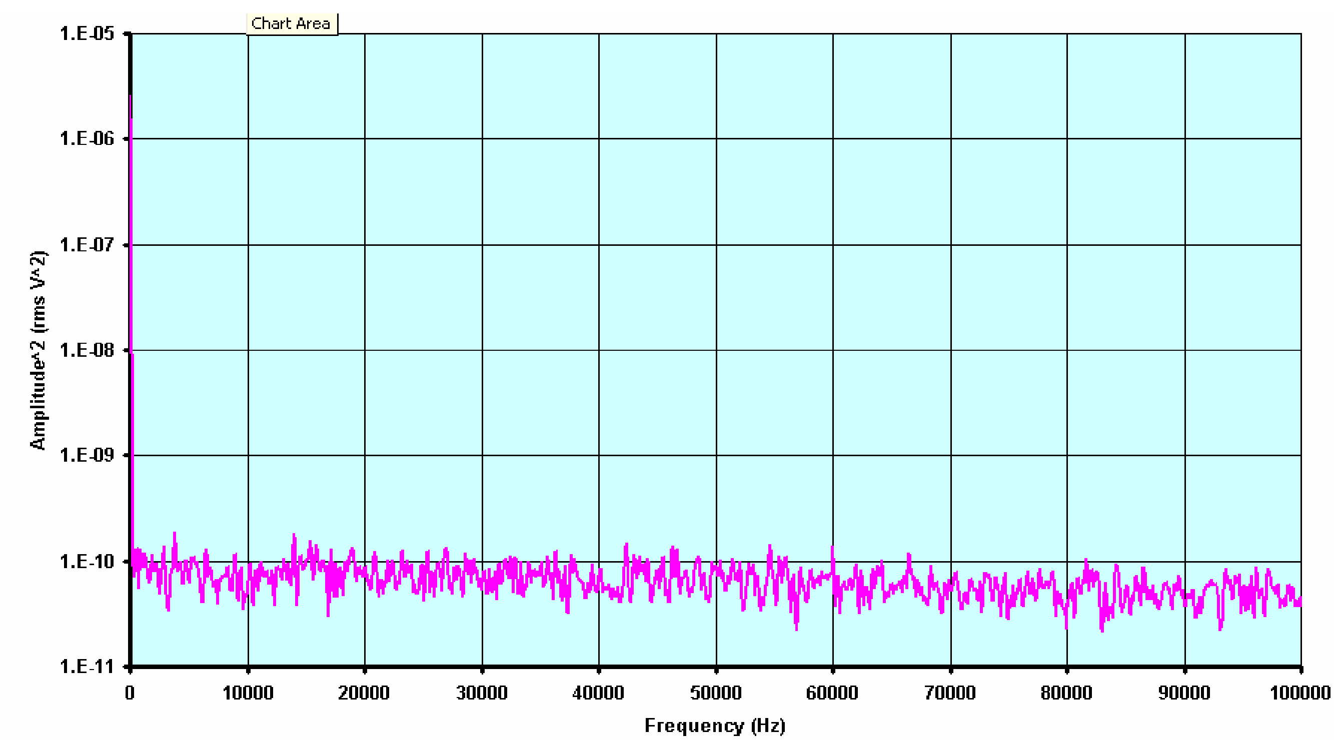

Fig 3.3.1 Modified 5E3 circuit; Floor noise level, amplifier off.

3.3.2 Noise floor at low frequencies

The next test conducted compared the noise floor levels in the frequency range of 0 to 800 Hz. This test was conducted with the amplifier turned on but with no input signal and both volume controls maxed and tone at its midway setting. The frequency range was chosen to isolate the 60 Hz hum and its harmonics. The graph shows that the highest amplitudes occur at 60 Hz, 120 Hz, and 180 Hz, 240 Hz, and 300 Hz. This verifies that the test is an accurate measurement of the hum associated with the 60 Hz power line input.

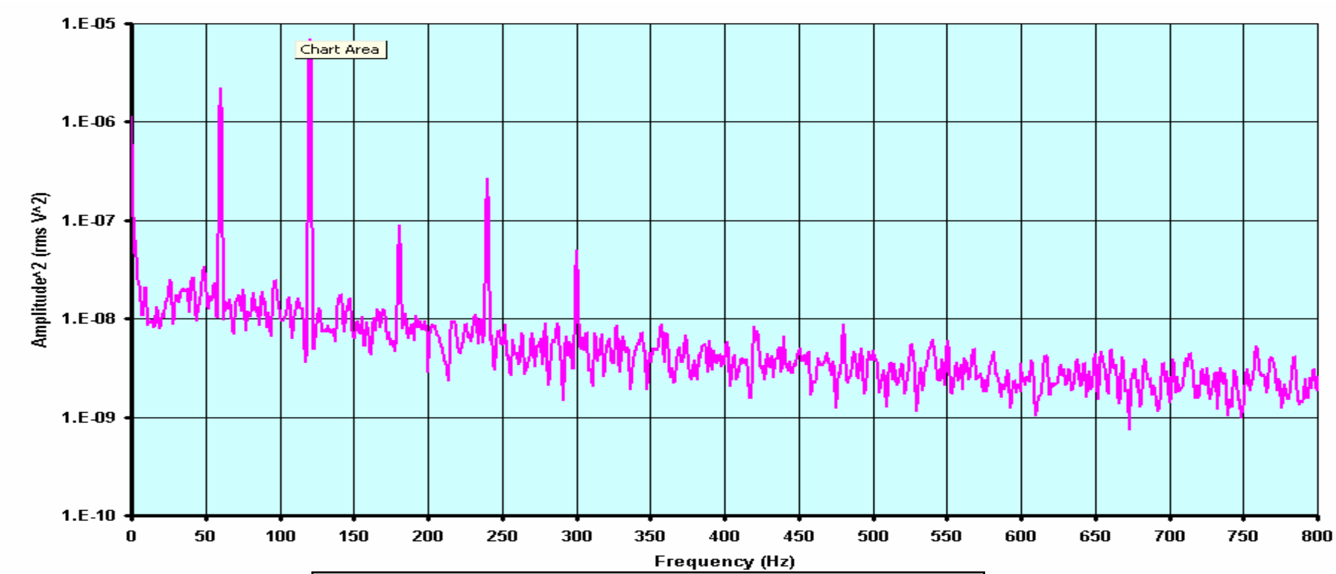

Fig. 3.3.2 Floor noise level at low frequencies

3.3.3 Noise floor level in the audio range

The range of the test was changed to include the full audio spectrum from 0 to 20 KHz. The test shows that the floor noise level with the amplifier on is higher in amplitude at the lower frequencies and decreases to a relatively steady value from 4 kHz to 20 KHz (Fig 3.3.3).

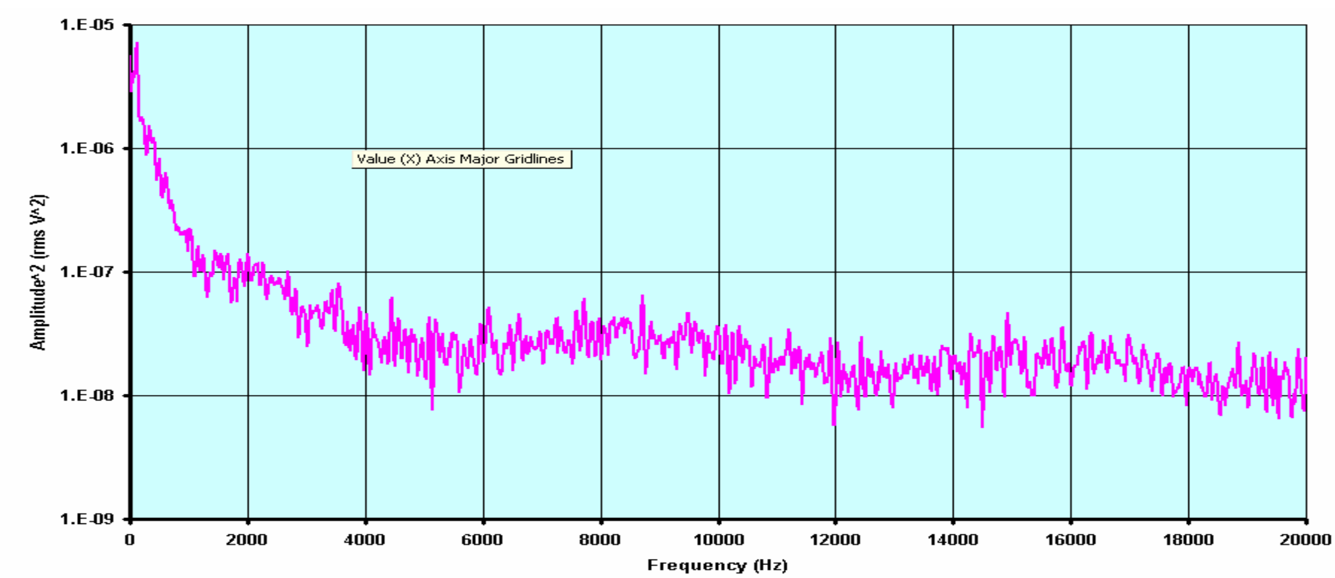

Fig. 3.3.3 Modified 5E3; Floor noise level in audio range

3.3.4 Floor noise level comparison

We conducted a comparison of the floor noise levels between our modified amplifier and an original Fender Tweed Deluxe (owned by Professor Errede) to show the differences in the overall circuit noise and higher level harmonics associated with 60 Hz hum and outside interference. The original amplifier emitted loud hum due to poor grounding practices and wiring techniques. This is a problem that we addressed in the fabrication of the amplifier and is verified by a comparison of the floor noise levels (Fig 3.3.4). The differences in amplitude at the various frequencies were converted to percentages and plotted (Fig. 3.3.5). This shows that the reduction in floor noise level and associated hum is about 75 % within the audio range and the overall difference is 55 %.

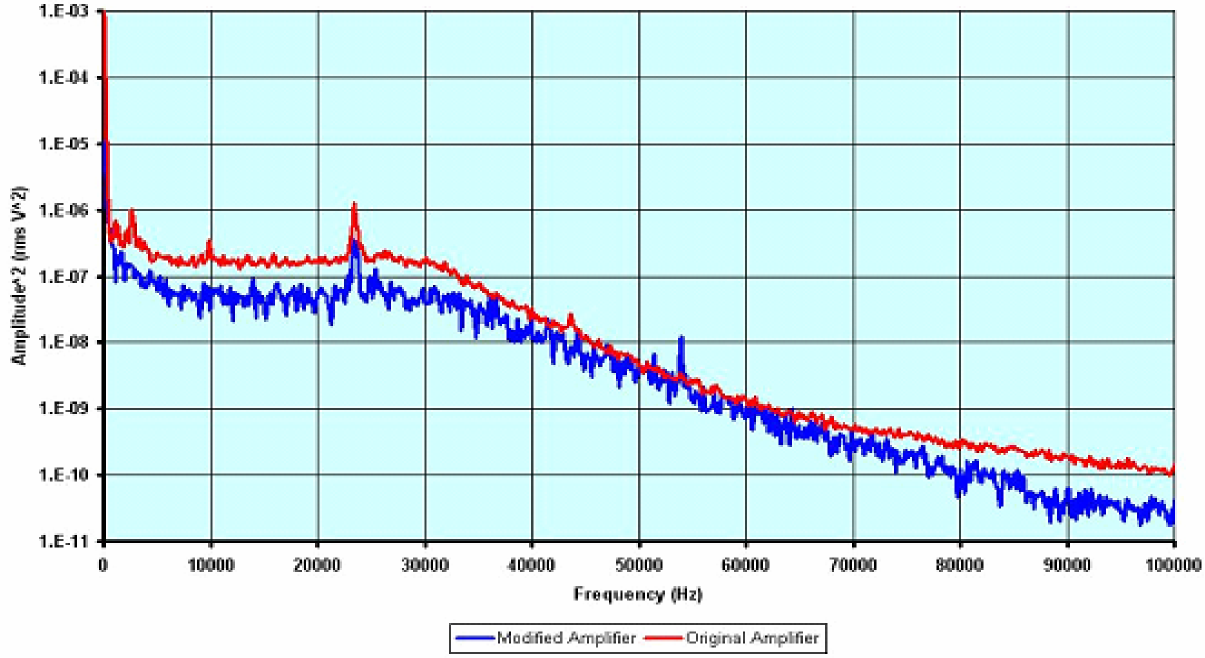

Fig. 3.3.4 Floor noise comparison, Original vs. Modified Fender 5E3 Tweed Deluxe (no 2nd stage cathode bypass capacitor; addition of feedback loop)

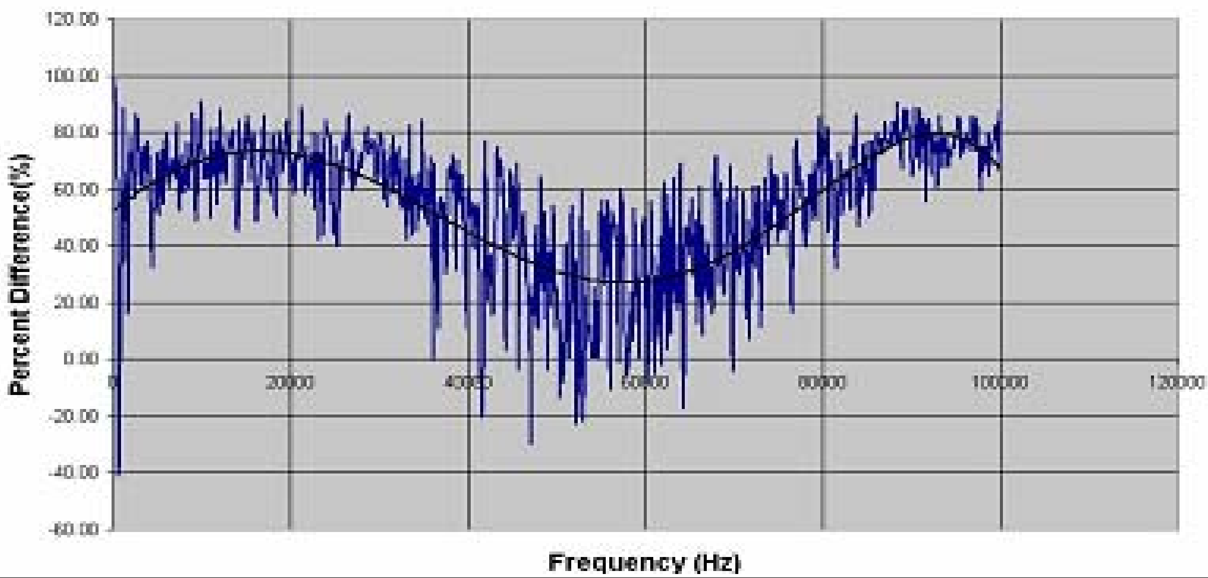

Fig. 3.3.5 Floor noise level percentage difference, Original vs. Modified. Fender Tweed Deluxe (no 2nd stage cathode bypass capacitor; addition of feedback loop)

3.4 FREQUENCY RESPONSE

The frequency response of the original circuit demonstrates that low frequencies are amplified more than high frequency when the tone level is at the midpoint. We wanted to flatten the frequency response so that all frequencies are amplified the same throughout the audio range when the tone level is at the midpoint. The addition of the feedback loop accomplished this by attenuating low frequencies more to achieve the flat mid-tone response (Table 3.4.1). The amplifier's frequency response was calculated by taking rms voltage measurements at the speaker terminal for varying frequencies and plotting the waveform (Fig. 3.4.1).

Table 3.4.1 Frequency response, voltage values at various frequencies

	without feedback loop			**with feedback loop**		
	(all knobs in 12 o'clock position)	(tone knob at min)	(tone knob at max)	(all knobs in 12 o'clock position)	(tone knob at min)	(tone knob at max)
Frequency (Hz)	**Rms voltage**	**Rms voltage**	**Rms voltage**	**Rms voltage**	**Rms voltage**	**Rms voltage**
10	0.44	0.45	0.425	0.529	0.53	0.518
20	1.103	1.17	1.026	0.974	1.002	0.937
50	1.712	2.045	1.564	1.147	1.264	1.146
100	1.6	1.91	1.55	1.03	1.16	1.212
200	1.534	1.317	1.628	0.965	0.881	1.301
500	1.847	0.696	2.009	1.087	0.516	1.631
1000	2.06	0.381	2.606	1.177	0.2925	2.142
2000	2.168	0.195	3.119	1.206	0.1534	2.601
5000	1.88	0.081	3.375	1.189	0.0636	2.834
10000	1.432	0.045	3.47	1.124	0.034	2.886
15000	1.212	0.0333	3.562	1.055	0.025	2.932
20000	1.094	0.0288	3.665	1.03	0.021	3.018

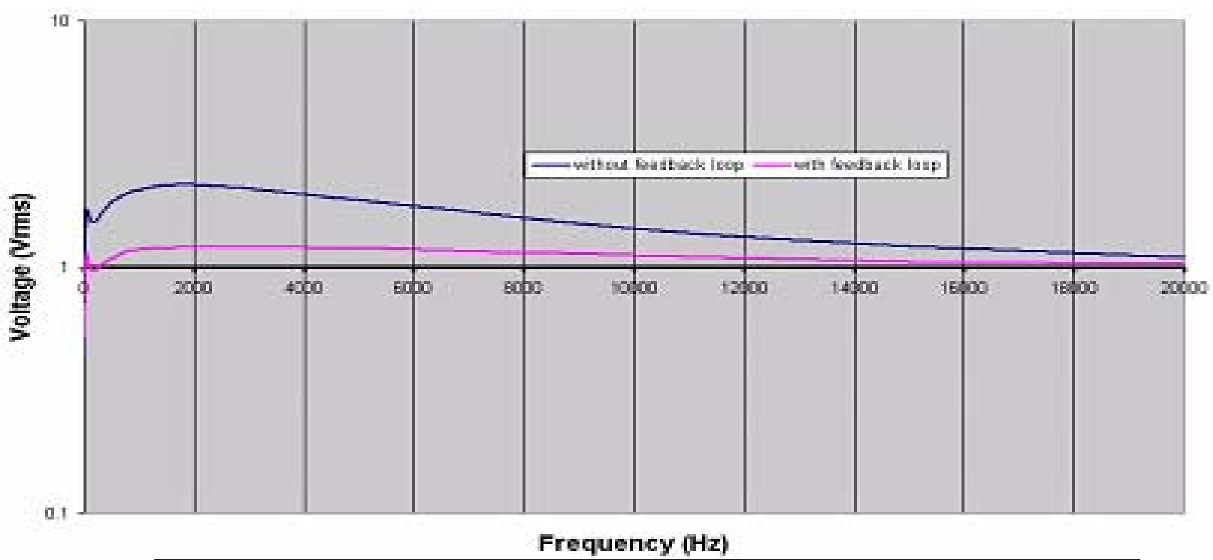

Fig. 3.4.1 Comparative Frequency response plot at mid-tone level.

3.5 VOLTAGE TESTS

To verify that all the stages were working properly, voltage measurements were taken before and after the first pre-amp, second pre-amp, and power stage. These measurements were taken at varying volume levels to quantify the relationship between gain and volume level. This data was gathered for the original and modified designs. Table 3.5 shows that the original design approach its maximum gain value much earlier that the modified versions. The signal voltage output did not increase much after its cutoff value, but instead further distorted the signal with increases in volume. The volume cutoff levels were the point where the gain began to saturate and distortion (overtones) were added. The volume cutoff levels were 2.3 for the original design, 4.7 with the cathode capacitor on the second pre-amp taken out, and 7.0 with the addition of the feedback loop to the circuit.

Table 3.5 Voltage measurements (Vrms), 100 mV 1 Khz signal input

Calculated Voltage Gains at Each Stage wihout cathode capacitor On second pre-amp stage

Gain stage	Volume Setting 2	Volume Setting 4	Volume Setting 10
1st preamp	11.03 V/V	39.36 V/V	54.16 V/V
2nd preamp	22.49 V/V	21.63 V/V	19.79 V/V
Overall	38.8 V/V	94.8 V/V	100.53 V/V
power stage	15.36 V/V	9.78 V/V	5.83 V/V
	Cuts off at volume = 4.7		

Calculated Voltage Gains at Each Stage for original design

Gain stage	Volume Setting 2	Volume Setting 4	Volume Setting 10
1st preamp	4.84 V/V	41.6 V/V	55.2 V/V
2nd preamp	56.52 V/V	46.59 V/V	29.27 V/V
overall	68.8 V/V	99.6 V/V	100.8 V/V
power stage	12.52 V/V	5.37 V/V	4.34 V/V
	Cuts off at volume = 2.3		

Calculated Voltage Gains at Each Stage with addition of feedback

Gain stage	Volume Setting 2	Volume Setting 4	Volume Setting 10
1st preamp	11.31 V/V	34.45 V/V	43.57 V/V
2nd preamp	17.78 V/V	19.37 V/V	20.81 V/V
overall	29.56 V/V	77.73 V/V	99.73 V/V
power stage	15.85 V/V	11.45 V/V	6.93 V/V
	Cuts off at volume = 7.0		

5. COST

5.1 Parts Cost

Part Description	Cost per Unit	Number Used	Total Cost
WeberVST 5E3 kit	$450.00	1	$450.00
Heat Shrink (1/4 inch., 1/8 inch.)	$0.25	22	$5.50
Carbon Composition Resistors	$0.25	24	$6.00
Aluminum Sheet Metal (14 inch. X 22 inch.)	$2.00	1	$2.00
Plastic Spacers	$0.25	4	$1.00
Star Washers	$0.25	4	$1.00
Coaxial Cable (2 feet)	$1.00	1	
			TOTAL PARTS = $466.50

5.2 Labor Cost

Building: (2 engineers) x ($25 per hour) x (50 hours) = $2,500[1]

Design: (2 engineers) x ($25 per hour) x (30 hours) = $1,500

Total Labor Cost = $4,000

Total Cost = Total Parts Cost + Labor Cost

Total Cost = 4,000 + 466.50 = 4,466.50

Note: The 5E3 kit includes chassis, cabinet, brass plate, fiber boards, 5Y3GT rectifying tube, 2 12AX7 tubes, 2 6V6GT tubes, tube sockets, carbon film resistors, capacitors, 3audio tapered potentiometers, 4 switches, 3 potentiometer knobs, fuse holder with 2 Amp slow blow fuse, 6 foot power cord with stress relief, pilot light and lamp, 4 input jacks, AlNiCo Signature 12 in. speaker, cloth covered wire, 5E3 output and power transformers.

[1] Faculty time = $0.00/hr of course!

6. CONCLUSIONS

After conducting the tests and analysis, we were satisfied that our goals were met. The noise was significantly reduced through a more thoughtful construction method, especially in the audible range of 10 Hz - 20 kHz. We were able to give more range on the volume potentiometer before the signal went into cutoff distortion by reducing the gain at the second stage with the eliminated capacitor and the addition of the feedback loop. The feedback loop also helped us to create a cleaner signal that went into cutoff at a much later volume setting. We also developed a more reliable and durable amplifier that operated its power circuit at much more reasonable dissipation levels and protected its tubes with a standby switch.

The quantifiable information is solid evidence that each of the listed problems were reduced or eliminated. However, by testing the amplifier and simultaneously testing the amp's sound with a guitar, it is hard to quantify a good sound because of its high subjectivity. We accomplished everything we set out to do and the sound of the amp was great, but in many instances the amp without the feedback loop sounded more interesting**.** In our opinions, leaving the 2nd stage cathode bypass capacitor off was better sounding because the distortion generated at higher volume levels (but not higher voltages) with the original 5E3 Deluxe circuit with 12AX7 1st stage preamp tubesounded very buzzy and unpleasant. The feedback loop creates a cleaner sound better suited toward hi-fi stereo and jazz music. Removing the feedback loop leaves an interesting crunchy distortion reminiscent of the old blues and rock of the 1950s and 1960s, a beautiful vintage sound. It is hard to say at what state of harmonics distortion and what level of cutoff the sound is most desirable because it is subject to each individual's opinion. We accomplished our desired goals and made careful analysis and proof. To another individual, some of the goals might have appeared fruitless as the original harsh, loud buzzy distortion generated by the large amplification of the amplifier with 1st stage 12AX7 and the absence of the feedback loop could have been favorable. One feasible option to deal with differing opinions is to insert a switch on the easily modified parts of our circuit. We can institute a switchable feedback loop as well as a switchable cathode capacitor at the second preamp stage triode. This way, the user has more control over reaching what they consider to be the optimal sound out of this particular amplifier.

We are confident that this modified implementation of the original Fender Tweed Deluxe will help hobbyists and musicians find a suitable replacement for a vintage 1950s 5E3. The scarcity of 12AY7 triodes makes it hard to recreate the sound of an original Tweed Deluxe, but by using a 12AX7 in its stead and performing our modifications we believe the amplifier sounds just as good. It is very possible to obtain 12AY7s on the internet at numerous places, but not at a local music store. The 12AX7 is a lot easier to obtain which is why people have chosen to use that as the 1st stage preamp tube. Likewise, one can also substitute other tubes (i.e. 5751) that have different amplification factors and behavioral characteristics so it is up to the user to decide which tube produces the best sound for this particular circuit. It is up to the user to experiment with different tubes and decide which sounds the best to *them*. There are many possibilities in such a relatively simple amplifier circuit. We feel that our modifications sound great. In addition, the improved reliability of the circuit should also please users as the amount of upkeep needed to maintain the amplifier is reduced.

Special Note: *We could not have done any of this without Professor Errede's knowledge, expertise, and skills. We probably would have ended up blowing something up, but with him guiding us, we were able to create a great sounding amp that built upon Fender's strong tradition. Hopefully the depth of this report will help him put his ideas and knowledge into publication.*

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[1] D. Torres, *Inside Tube Amps*. San Mateo: Sparpco Inc., 1995.

[2] K. O'Connor, *The Ultimate Tone Vol.1*. London: Power Press Publishing, 1995.

[3] Aiken Amplifiers, "Designing for Global Negative Feedback" December 1995, http-://www.aikenamps.com/GlobalNegativeFeedback.htm.

[4] K. O'Connor, *The Ultimate Tone Vol.3*. London: Power Press Publishing, 2002