60 Watt Class AB_1 Vacuum Tube Amplifier

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An Independent Study Project With Prof. Errede.

Since I began playing guitar, I have always played through a solid state amp due to the much cheaper cost. But after hearing a tube amp, I understood why they are still made and why they draw such a hefty price tag. Since then I have always wanted to own one, but have never had the money to realize that dream. So, when I got the chance to build one as an independent study project with Prof. Steve Errede, I jumped on it.

Research:

Due to my very limited experience with vacuum tubes, I purchased three books by Kevin O'Connor (The Ultimate Tone I, The Ultimate Tone II, and Principles of Power), as suggested by Prof. Errede. These books gave a background on vacuum tubes and also their applications to guitar amplifiers. After reading these books, I felt that I was ready to start designing the amp.

Design:

Coming into the project, I knew that I wanted an amp with roughly 60 watts of output that had two preamp channels with separate tone controls. From this starting point, I was able to come up with a circuit that would meet these needs. I first looked at the power amp circuit. To get 60 watts output, I decided to use two 6L6 beam power pentodes in a class AB_1 push-pull but cathode biased configuration. This style of amp uses two out of phase signals to drive the pair of output devices, which are then coupled to the loudspeakers by an output transformer. The major elements needed for this type of power amp are a phase splitter, a power amplifier, and an output transformer. The specific configuration that I initially choose is very similar to the power amp section of 50's era Fender Tweed amplifiers (i.e. Fender Pro, schematic 5C5). Unlike many companies that mass produce guitar amplifiers, I used a very large output transformer. The smaller transformers that major amp manufacturers use tend to have core saturation at very low input levels which leads to a very unpleasant sounding distortion. The output transformer I purchased was a Hammond 1650R. This transformer has big-iron laminations, interleaved windings, and very high inductance. The inductance is so high, in fact, that it is approximately 4.5 times larger than the inductance of large Fender output transformers (i.e. Twin and Tonemaster output transformers). The combination of very high inductance and big-iron laminations gives the transformer a very good bottom end response. The interleaved windings lead to very low leakage and therefore a good high end response. Overall, the response of the transformer is very flat from 20 to 30 KHz. In addition to these properties, this transformer has a primary with a center tap and also 42% ultra linear screen taps and can handle 100 Watts of output with secondary windings for 4, 8, or 16 Ohms. I initially choose not to use the ultra linear screen taps, but I left them intact in case I want to squeeze more power out of the amp. After taking care of the power amp and the output transformer, I focused on the phase inverter. I went through all the various types of phase inverters and finally decided on the long tailed pair. This uses two triodes, in my case 12AX7s, to derive the two out of phase signals needed for the AB_1 configuration.

Once the power amp design was complete, I turned to the preamp. I decided to stick with 12AX7s, since I was already using them in the phase splitter and they seem to be the tube of choice for preamps. To get a drive channel and a clean channel, I decided to use two gain stages for the clean channel and three for drive. With proper switching, this led to a total of three triodes. Since 12AX7s are dual triodes, this would leave one triode unused. Prof. Errede recommended that I use the last tube as a unity gain buffer in the drive channel. For the equalization, I used a Fender style three band equalizer on each channel. This design fulfilled all of my original requirements.

The last part of the design was to supply power to the amp. The power supply had to supply the high DC plate and screen voltages for the circuit and also the low AC heater voltages. In order to get all the voltages necessary, I used a Hammond power transformer (273X). This simplified the power supply design since it has a high voltage winding as well as separate windings for the heater voltages. I then needed to rectify the main secondary winding to get the high DC voltages for the tubes. Since the high voltage winding on the transformer was center tapped, I used a full wave center tapped rectifier configuration. I decided to use solid state diodes for the rectifiers since they are smaller than tube diodes and I have had prior experience with them. Since solid state diodes have extremely fast power up times, I added a standby switch to the circuit to protect the tubes from the high plate voltages. After rectification several pi filters were used to smooth the outputs and provide the different voltages needed. The filters were designed with very long time constants to keep the output voltage as close to DC as possible. Table 1 shows the time constants for each of these filters. Note that these calculations may be inaccurate since the output resistances of the tubes are not constant.

Table 1: Pi Filter Time Constants

Filter	Time Constant (s)
First Pi Filter	17.6
Second Pi Filter	17.6
Third Pi Filter	6.4
Fourth Pi Filter	2

After coming up with the design, I began ordering the components needed. The first parts I ordered were the transformers. When they arrived, I took them into Prof. Errede and we tested them. I was very pleased to see that the leakage for the output transformer was extremely low. Table 2 shows the results for the power transformer. Tables 3, 4, and 5 show the results for the output transformer with a 1 KHz input. A.1 and A.2 show the rest of the results for the output transformer. Equations 1, 2, and 3 were used to calculate parameters for the transformer tests. I also ordered the tubes at this point, since I knew which types I would be using. I decided to go with Groove Tubes (GT) for all the tubes I ordered. I used GT 12AX7-Cs for the dual triodes and a matched pair of GT 6L6-GCs (with a distortion rating of 7) for the beam power pentodes. After the larger components were ordered, I focused on the resistors and capacitors. In an effort to get the sound of a 50s/60s era amp, I decided to use carbon composition resistors rather than a newer style of resistors. I could not find high power (5W and up) carbon composition resistors, but these few resistors were not in the critical signal path so I choose what was available, wire-wound. For the capacitors, I avoided the use of ceramic types and instead used only silver mica, Sprague “Orange Drop” 715 metallized polypropylene, or Sprague “Atomlytic” electrolytic capacitors.

Table 2: Hammond 273X Power Transformer Tests

Winding (Diagram given in A.10)	DC Resistance (Ohms)
Primary (BLK – BLK)	2.6
5.0V Secondary (YEL – YEL)	0.1
6.3V Secondary (GRN – GRN)	0.2
Main Secondary (RED – YEL)	82
Main Secondary (YEL – RED)	89.7
Main Secondary (RED – RED)	171.8

$$Z_{Load}^{pri} = \left(\frac{V^{pri}}{V^{\sec}} \right)^2 \times Z_{Load}^{\sec} \qquad \textbf{Equation 1}$$

$$Z_{Load}^{pri} = \left(\frac{L_{BLU-BRN}^{pri-oc}}{L_{4,8,16Ohm}^{\sec-oc}} \right) \times Z_{Load}^{\sec} \qquad \textbf{Equation 2}$$

$$TurnsRatio = \frac{V^{pri}}{V^{\sec}} = \sqrt{\frac{L_{BLU-BRN}^{pri-oc}}{L_{4,8,16Ohm}^{\sec-oc}}} \qquad \textbf{Equation 3}$$

Table 3: Hammond 1650R Output Transformer DC Resistances

Winding (Diagram given in A.11)	DC Resistance (Ohms)
Primary (BLU – BRN)	103
Primary (BLU – RED)	55.6
Primary (BRN – RED)	47.4
Primary (BLU/YEL – RED)	21.8
Primary (BRN/YEL – RED)	21.7
Secondary (YEL – GRN/YEL)	0.1
Secondary (BLK/YEL – GRN/YEL)	0.2
Secondary (BLK/YEL – YEL)	0.4
Secondary (GRN – BLK)	0.2

Table 4: Hammond 1650R Transformer Inductances for 1KHz.

Winding (Diagram given in A.11)	Open Circuit Inductances (H)	Short Circuit Inductances (mH)	% Leakage	Turns Ratio	Plate Load Impedance (Ohm)
Lpri (BLU – RED)	18.5	6.85	0.037	N/A	N/A
Lpri (BRN – RED)	17.8	4.89	0.027	N/A	N/A
Lpri (BLU – BRN)	55.8	11.52	0.021	N/A	N/A
Lsec (GRN – BLK)	0.0411	0.0192	0.047	36.85	N/A
Lsec (GRN/YEL – BLK/YEL)	0.049	0.0239	0.049	33.75	N/A
Lsec (BLK/YEL – YEL)	0.092	0.0252	0.027	24.63	N/A
Lsec (GRN/YEL – YEL)	0.008	0.0098	0.123	83.52	N/A
Lsec (4 Ohm)	0.0445	0.013	0.029	35.41	5015
Lsec (8 Ohm)	0.0905	0.0223	0.025	24.83	4933
Lsec (16 Ohm)	0.1811	0.0379	0.021	17.55	4930

Table 5: Hammond 1650R AC Voltage Measurements with Vacpri = 10.03 V @ 1KHz

Winding (Diagram given in A.11)	Secondary Voltage (Vac)	Turns Ratio	Plate Load Impedance (Ohms)
GRN – BLK	0.2808	35.72	N/A
GRN/YEL – BLK/YEL	0.2816	35.62	N/A
BLK/YEL – YEL	0.4015	24.98	N/A
GRN/YEL – YEL	0.1187	84.50	N/A
4 Ohm	0.2805	35.76	5114
8 Ohm	0.3977	25.22	5088
16 Ohm	0.5635	17.80	5069

Construction:

The only part left to be ordered was the chassis, but before I could order this, I needed to come up with a layout diagram. I came up with a rough layout diagram and decided that a chassis on the order of 17” x 8” x 4” would be needed. I ordered this size but I received a much smaller 12” x 8” x 2” chassis. This forced me to rethink my layout diagram and when I finished it, I was left with a very cramped chassis. I thought that this might add more noise to the circuit, but by using proper grounding techniques (discussed later in this paper) the noise was kept to a minimum. From here, I began punching the chassis with a drill and Greenleaf punches. I also started wiring up the main part of the circuit on a reused PCB from an old equalizer. With these completed, I started mounting everything in the chassis and wiring the circuit to the transformers, tubes, and controls. For all critical signal path wires, I used heavily shielded RG-174 coaxial cable to prevent the addition of unwanted noise. In order to properly do this, I used Prof. Errede's method of star grounding. This consists of returning all electrical power to its source as directly as possible. Once this is accomplished, these "local" grounds are then tied to a common star ground on the chassis. Applying this method of grounding drastically reduces the noise injected into the amp through ground loops. In order to properly implement this method, isolated input and output jacks must be used. I choose isolated, ground interrupt Marshall-style mono input and output jacks with the guitar grounded to the local ground of the first stage preamp tube. For the coax, one end of the shielding braid was tied to the "closest" local ground. With all wiring complete it was time to test the amp.

Debug:

Prof. Errede inspected the amp and helped with power up. He pointed out some issues I had with the coax. These dealt with how to use heat shrink tubing properly in order to prevent shorts. After fixing this and checking all solder connections for quality, we powered it on. I was pleased to see that there was no catastrophic failure and that the amplifier actually functioned properly.

Even though the amp functioned properly, there were some noticeable problems which needed to be addressed. The first issue was with heat and power dissipation in the power tubes. We measured the static power dissipation and saw that it was at the higher end of the tolerance range. The fix for this was to use a higher value of cathode resistor to limit the current (and hence the power) flowing through the tubes. Even after swapping the resistor, there was still a good amount of heat coming off of the power tubes. Prof. Errede suggested using fans to blow air across the tubes in an effort to cool them off. I took his advice and added two fans. The next problem was oscillations and heavy distortion in the amp. There were actually two oscillations. One was a low frequency oscillation that occurred in the drive channel when all controls on this channel were set at a maximum. The other one was a high frequency oscillation that occurred in the drive channel when a large input signal was observed. After testing the amp thoroughly, we discovered that there were some grounding issues. I had properly applied the grounding technique to the circuit grounds, but for the coax I used a star ground. This introduced a lot of stray capacitance which we figured was leading to the high frequency oscillation. After applying proper grounding techniques to the coax shielding, we noticed that the oscillation did not entirely go away. The next thought was that it was caused by too much gain. Therefore we removed all the cathode bypass capacitors. This reduced distortion in the amp and also got rid of both of the oscillations. A third problem observed was that there was still too much gain in the clean channel. This was easily observable since the amp broke up at higher (above half of max) volume levels. I decided that using a lower gain tube would be the best way to fix this. Therefore, I swapped the first and last preamp stage tube with a 12AT7, which has lower gain than the AX. This worked at decreasing the gain, but the 12AT7 has a different set of plate family curves, which lead to a slightly more bassy output. Prof. Errede suggested that I try a 5751 in this position as it is more like the 12AX7 but with a lower gain.

Measurements and Calculations:

Once I was satisfied with the circuit, Prof. Errede helped me perform extensive measurements of the circuit. The first set of measurements taken was DC measurements. The DC voltages at all the tubes and at all the pi filter outputs of the power supply were measured. From these measurements, we can calculate the DC power dissipation in the output tubes. Equations 4 and 5 can be used to calculate the power dissipation. Table 6 shows the DC voltages at each of the pi filters and Table 7 shows the node voltages for all the tubes. Table 8 shows the power dissipation in the output tubes.

Table 6: Output voltages in the power supply

Voltage (Schematic given in A.??)	Volts DC (VDC)
VB^+ at Standby	563
VB^+ at Operate	508
V1k	494
V22k1	369
V22k2	442

Table 7: Node Voltages for all Tubes.

Tube	Function	Vgrid (V)	Vk (V)	Vscreen (V)	Vplate (V)
V1A	Gain (Preamp)	0	2.73	N/A	173.9
V1B	Gain (Preamp)	0	2.714	N/A	167.6
V2A	Gain (Preamp)	0	2.528	N/A	281.9
V2B	Buffer (Preamp)	126.6*	128.9	N/A	369
V3A	Phase Splitter	56.9*	59	N/A	311
V3B	Phase Splitter	56.9*	59	N/A	309.3
V4	Power Amp	0	56.2	495	505
V5	Power Amp	0	56.2	495	506

* These voltages were taken at the nearest measurable points and are not exactly accurate.

$$I_K = \frac{1}{2} \times \left(\frac{V_K}{R_K} \right) \qquad \text{Equation 4}$$

$$P_{Diss} = \left(V_{Plate} - V_K \right) \times I_K \qquad \text{Equation 5}$$

Table 8: Power Dissipation in the Output Tubes

Tube	Ik (mA)	Pdiss (W)
V4	31.22	14.11
V5	31.22	14.11

After taking the DC measurements, AC measurements were performed. Measuring output voltage of the amplifier at the speaker terminal with a non-inductive 8 Ohm load, noise floor, frequency response, and overall gain at varying control levels were measured. For the noise floor of the amp, we applied no input and varied the controls to observe the effects. Figures showing this series of measurements are shown in A.3- A.5 of the appendix. Note that the amp is very quiet. The only sources of noise are from the power supply and the room where the measurements were taken (6105 ESB). The noise from the supply is evident in the 0-800Hz plots, where the spikes at multiples of 60Hz are very clear. The room noise is obvious from the 0-100KHz plots, where the high frequency spikes are due to computers, LAN, and other things in the room. For the frequency response, we used a DMM to check the AC RMS voltage at the output with varying input frequencies. Figures displaying the series of measurements performed are shown in A.6 and A.7 of the appendix. Finally output waveforms are shown in A.8 (clean) and A.9 (drive) with a 1 KHz input at 100mV peak. After taking all the AC measurements, an estimated output power can be computed. Equation 6 shows how to calculate output power and A.12 shows the data used and the results. Note that the actual power generated by the power tubes is a factor of 2× that measured at the speaker load, since the maximum theoretical efficiency of transferring power from the power tubes to the speaker load (via the output transformer, for perfect impedance-matching) is 50%.

$$P_{Out} = \frac{\left(V_{RMS}\right)^2}{8} \qquad \text{Equation 6}$$

Finally the schematic is shown in A.13 of the appendix. Pictures of the amp are also shown in A.14-A.19. I intend to purchase knobs and a faceplate for the head and cover both the speaker cabinet and the head in black tolex.

References

1. Prof. Steve Errede, Invaluable instruction throughout entire process.
2. Kevin O’Connor, The Ultimate Tone I. London Press.
3. Kevin O’Connor, The Ultimate Tone II. London Press.
4. Kevin O’Connor, Principles of Power. London Press.
5. Mr. Ben Juday, Many of the rarer parts for the project.

Appendix

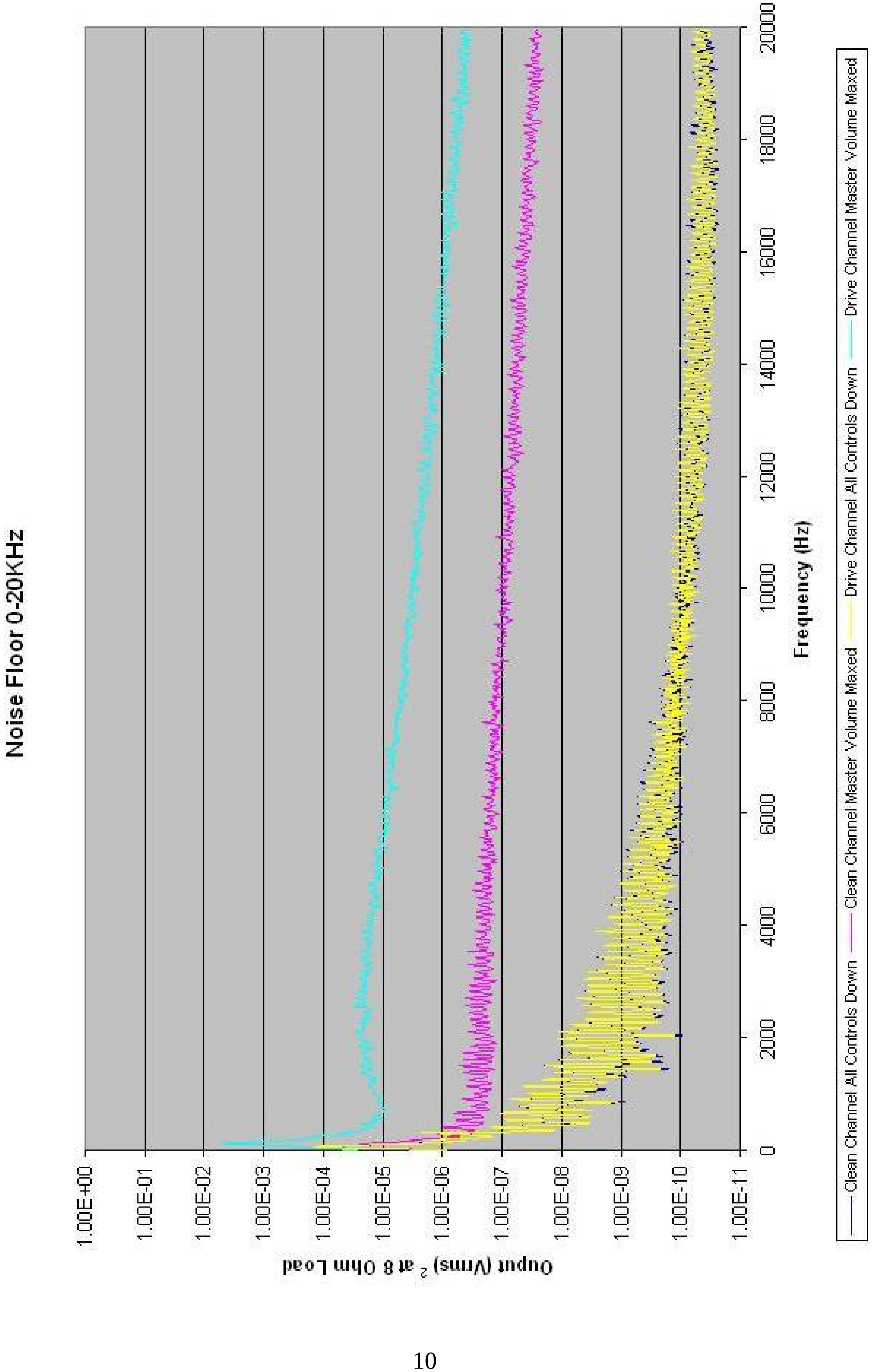
A.1: Hammond 1650R Transformer Dissipations at 1KHz

Winding (Diagram given in A.32)	Open Circuit Dissipations	Short Circuit Dissipation
Dpri (BLU – RED)	0.506	2.41
Dpri (BRN – RED)	0.489	2.69
Dpri (BLU – BRN)	0.351	3.3
Dsec (GRN – BLK)	0.37	2.78
Dsec (GRN/YEL – BLK/YEL)	0.416	2.65
Dsec (BLK/YEL – YEL)	0.49	3.38
Dsec (GRN/YEL – YEL)	0.43	2.1
Dsec (4 Ohm)	0.429	2.97
Dsec (8 Ohm)	0.48	2.86
Dsec (16 Ohm)	0.555	3.45

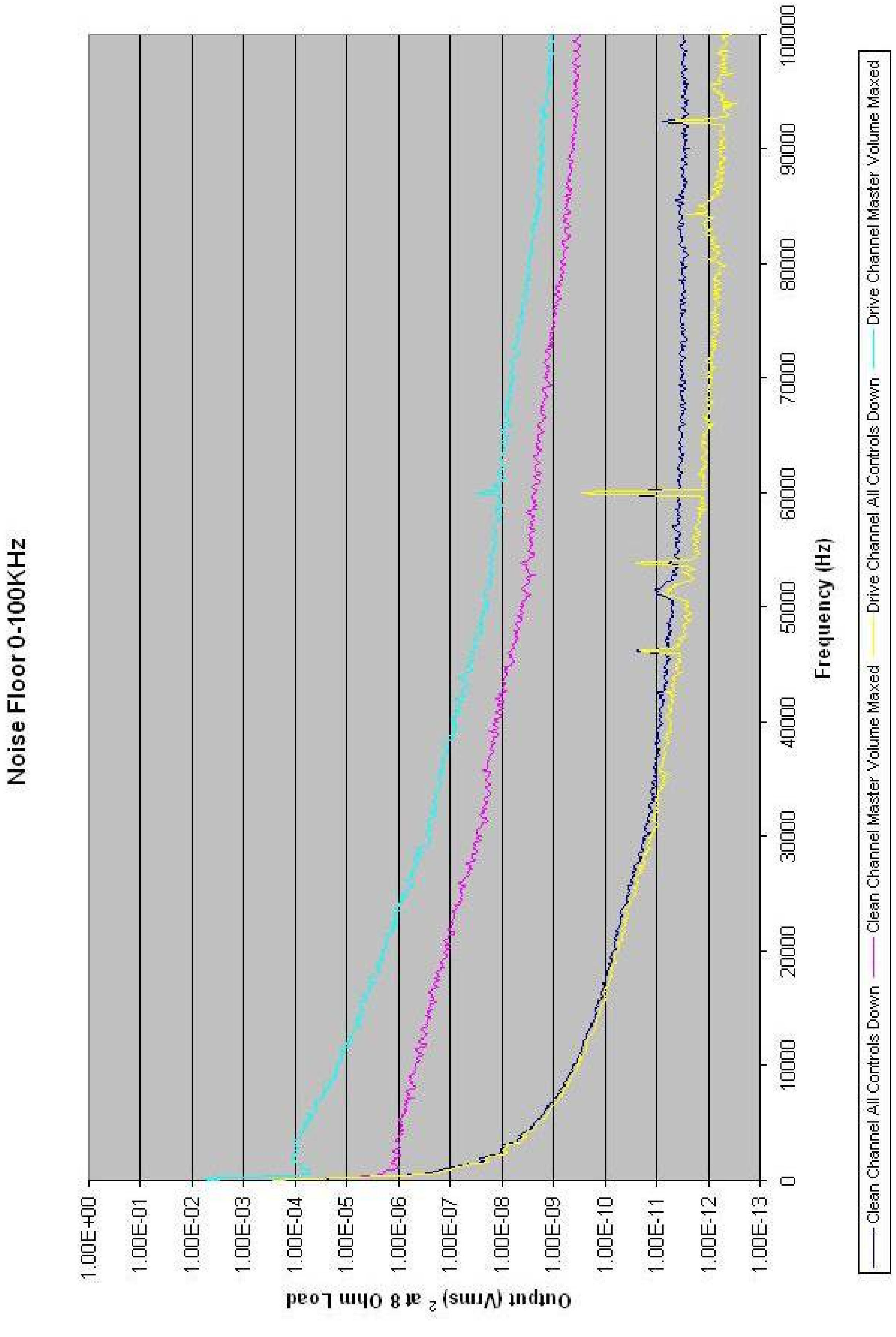
A.2: Hammond 1650R Transformer Tests at 120Hz and 10KHz

Winding (Diagram given in A.32)	Open Circuit	Short Circuit	Short Circuit	% Leakage	Turns Ratio	Plate Load Impedance (Ohm)
	120Hz	120Hz	10KHz	120Hz	120Hz	120Hz
Lpri (BLU – RED)	5.47 H	10.8 mH	5.3 mH	0.197	N/A	N/A
Dpri (BLU – RED)	0.058	10.85	0.401	N/A	N/A	N/A
Lpri (BRN – RED)	5.42 H	5.75 mH	4.46 mH	0.106	N/A	N/A
Dpri (BRN – RED)	0.062	>20	0.374	N/A	N/A	N/A
Lpri (BLU – BRN)	21.8 H	14.4 mH	11.11 mH	0.066	N/A	N/A
Dpri (BLU – BRN)	0.377	>20	0.404	N/A	N/A	N/A
Lsec (GRN – BLK)	0.0428 H	0.04 mH	0.016 mH	0.0935	22.57	N/A
Dsec (GRN – BLK)	0.434	>20	0.409	N/A	N/A	N/A
Lsec (GRN/YEL – BLK/YEL)	0.0695 H	0.051 mH	0.019 mH	0.0734	17.71	N/A
Dsec (GRN/YEL – BLK/YEL)	0.572	>20	0.452	N/A	N/A	N/A
Lsec (BLK/YEL – YEL)	0.1825 H	0.047 mH	0.021 mH	0.0258	10.93	N/A
Dsec (BLK/YEL – YEL)	0.687	>20	0.461	N/A	N/A	N/A
Lsec (GRN/YEL – YEL)	3.4 H	0.011 mH	0.008 mH	0.0003	2.53	N/A
Dsec (GRN/YEL – YEL)	>20	>20	0.436	N/A	N/A	N/A
Lsec (4 Ohm)	0.0577 H	0.017 mH	0.012 mH	0.0295	19.44	1511
Dsec (4 Ohm)	0.518	>20	0.37	N/A	N/A	N/A
Lsec (8 Ohm)	0.1809 H	0.026 mH	0.02 mH	0.0144	10.98	964
Dsec (8 Ohm)	0.686	>20	0.382	N/A	N/A	N/A
Lsec (16 Ohm)	0.069 H	0.042 mH	0.037 mH	0.0609	17.77	5055
Dsec (16 Ohm)	>20	>20	0.406	N/A	N/A	N/A

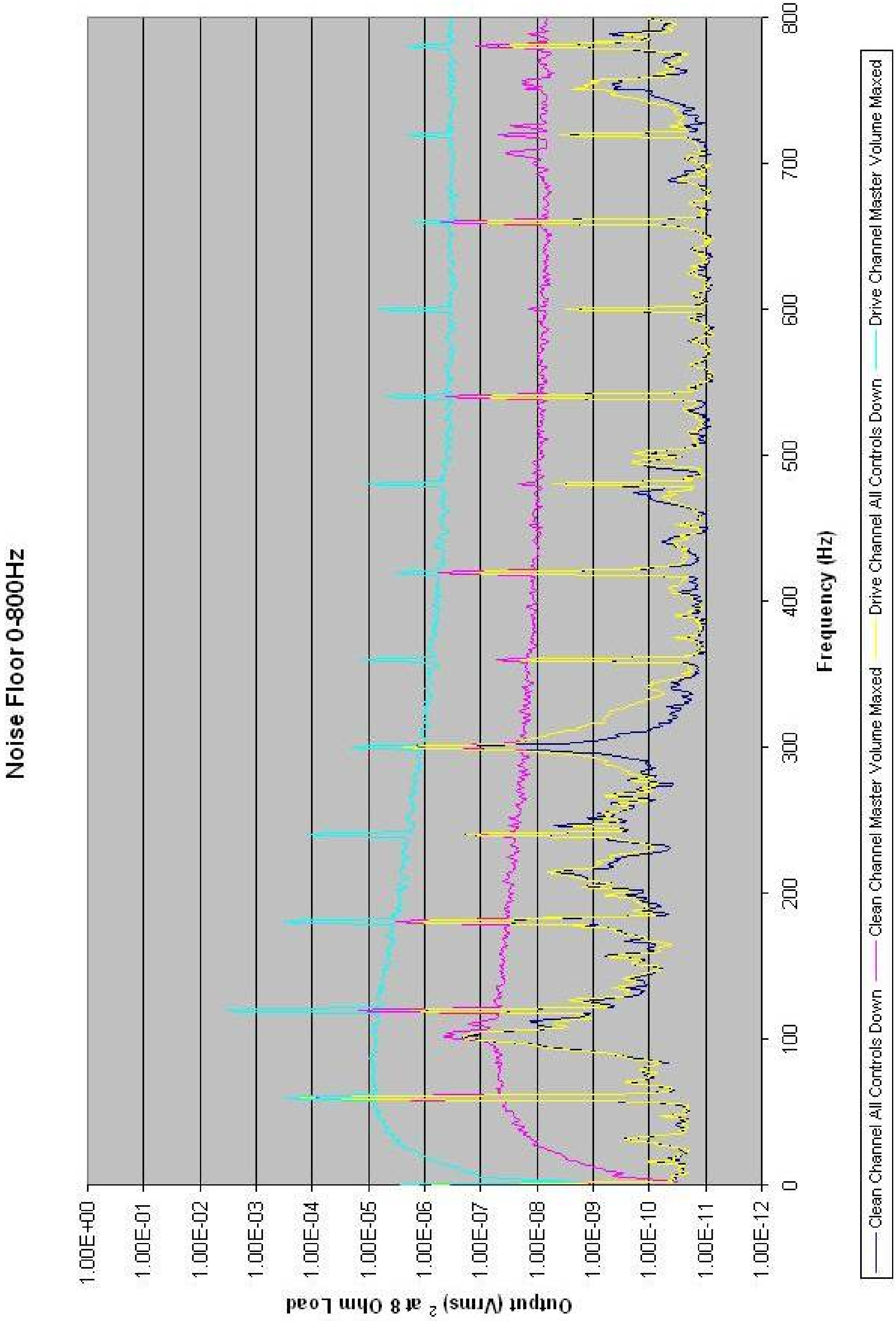
A.3


Noise Floor 0-20KHz
Ouput (Vrms) ² at 8 Ohm Load
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Frequency (Hz)
Clean Channel All Controls Down
Clean Channel Master Volume Maxed
Drive Channel All Controls Down
Drive Channel Master Volume Maxed

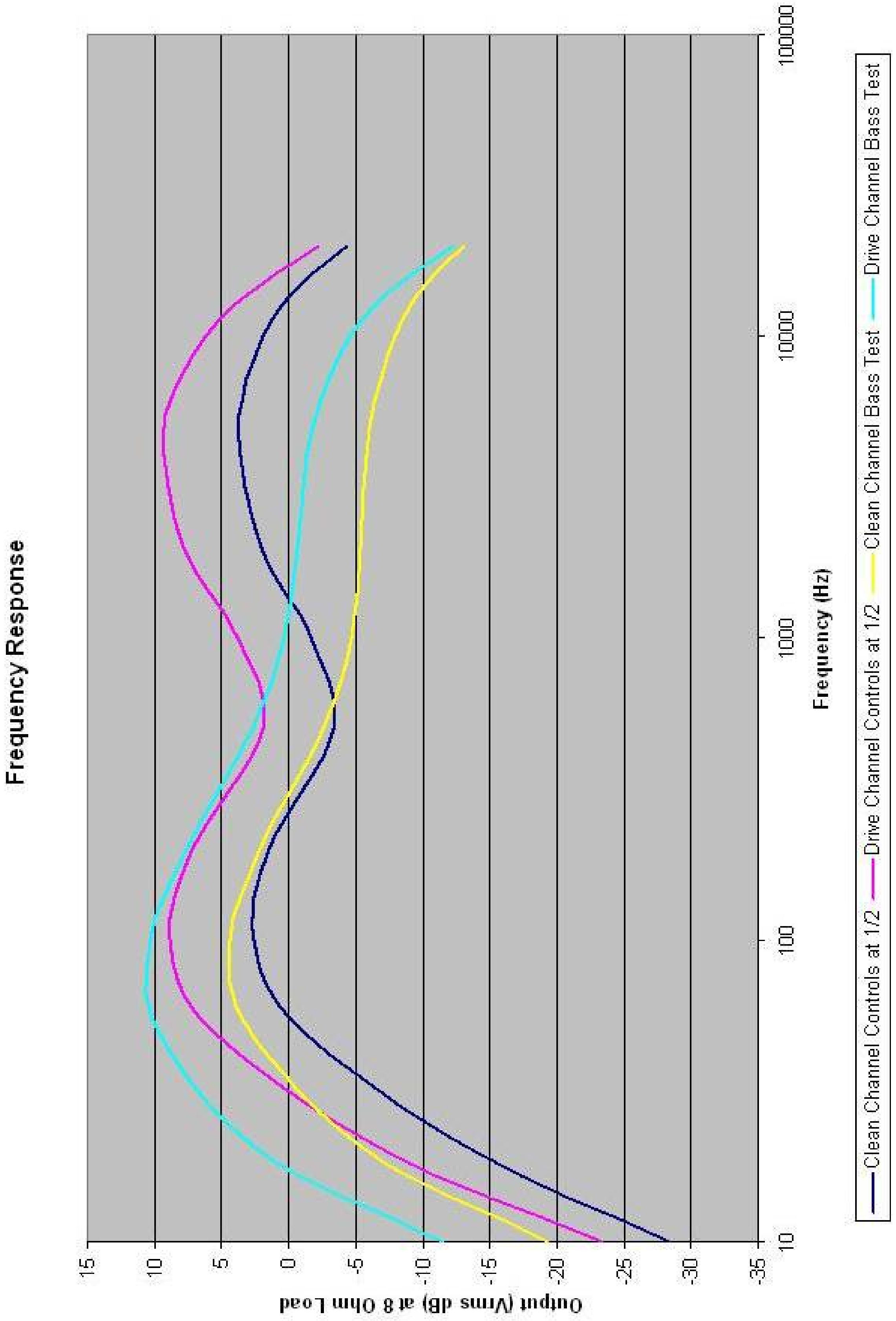
A.4


Noise Floor 0-100KHz
Output (Vrms) 2 at 8 Ohm Load
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
Frequency (Hz)
Clean Channel All Controls Down
Clean Channel Master Volume Maxed
Drive Channel All Controls Down
Drive Channel Master Volume Maxed

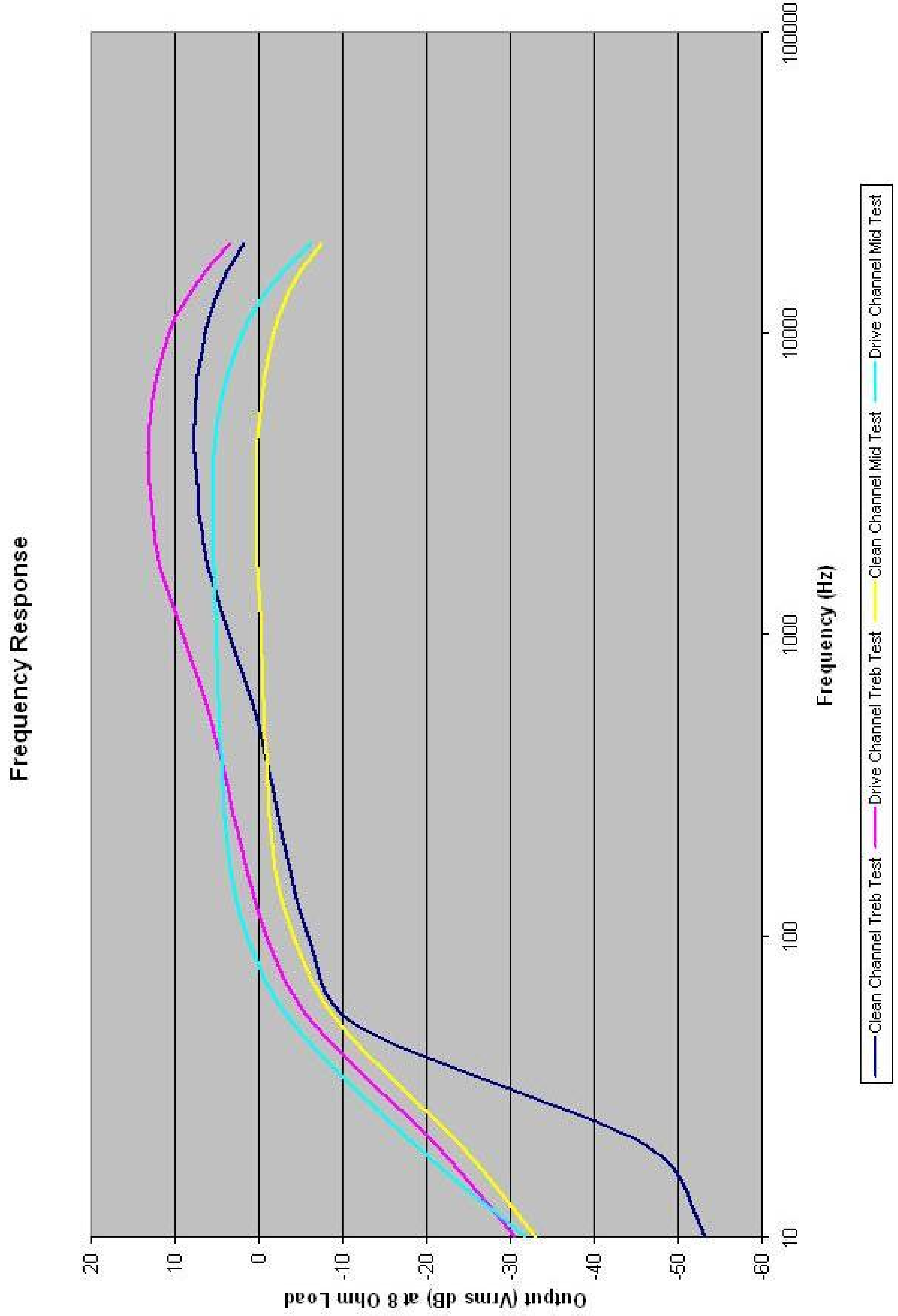
A.5


Noise Floor 0-800Hz
Output (Vrms) 2 at 8 Ohm Load
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
0
100
200
300
400
500
600
700
800
Frequency (Hz)
Clean Channel All Controls Down
Clean Channel Master Volume Maxed
Drive Channel All Controls Down
Drive Channel Master Volume Maxed

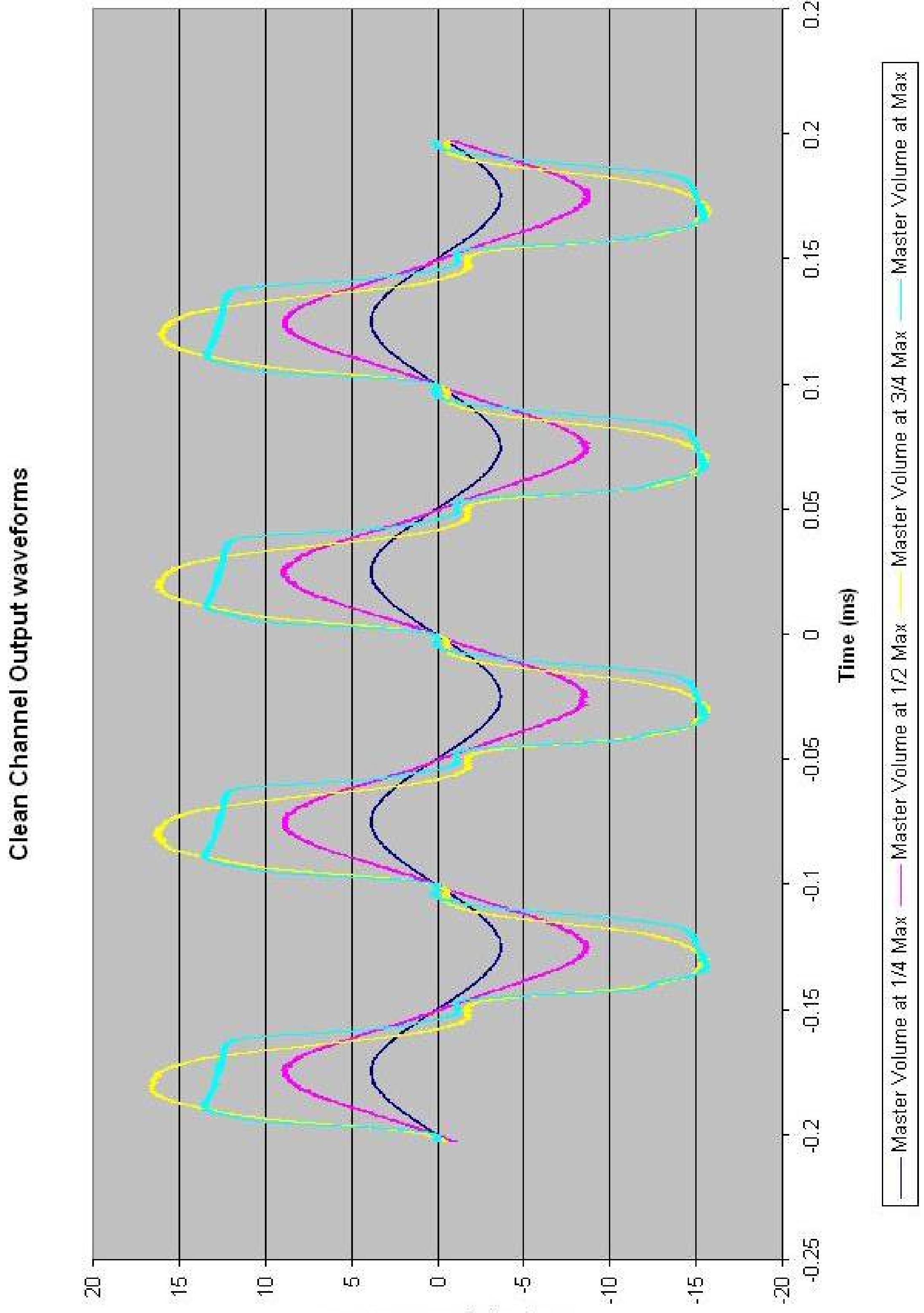
A.6


Frequency Response
Output (Vrms dB) at 8 Ohm Load
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
10
100
1000
10000
100000
Frequency (Hz)
Clean Channel Controls at 1/2
Drive Channel Controls at 1/2
Clean Channel Bass Test
Drive Channel Bass Test

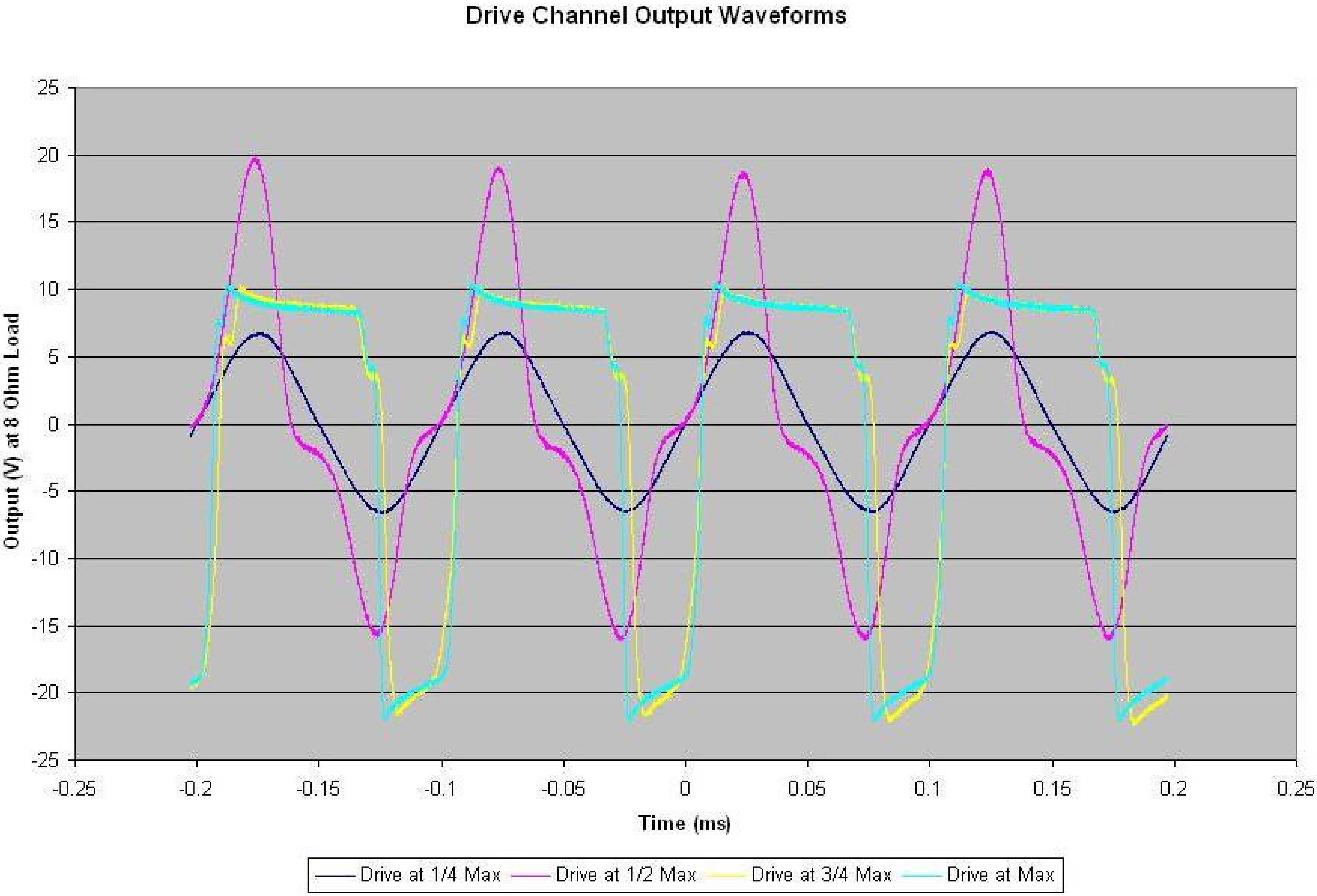
A.7


Frequency Response
Output (Vrms dB) at 8 Ohm Load
20
10
0
-10
-20
-30
-40
-50
-60
Frequency (Hz)
10
100
1000
10000
100000
Clean Channel Treb Test
Drive Channel Treb Test
Clean Channel Mid Test
Drive Channel Mid Test

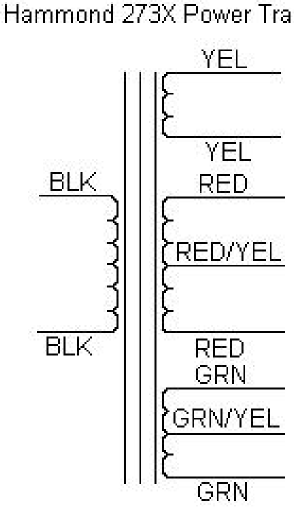
A.8


Clean Channel Output waveforms
Output (V) at 8 Ohm Load
20
15
10
5
0
-5
-10
-15
-20
Time (ms)
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
Master Volume at 1/4 Max
Master Volume at 1/2 Max
Master Volume at 3/4 Max
Master Volume at Max

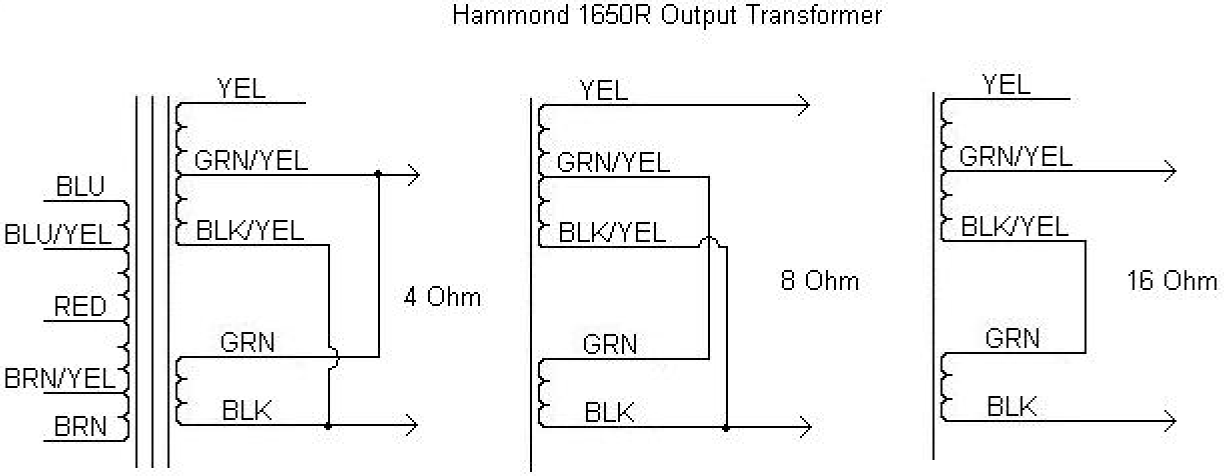
A.9


Drive Channel Output Waveforms
Output (V) at 8 Ohm Load
25
20
15
10
5
0
-5
-10
-15
-20
-25
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
Time (ms)
Drive at 1/4 Max
Drive at 1/2 Max
Drive at 3/4 Max
Drive at Max

A.10: Winding Diagram for Hammond 273X Power Transformer



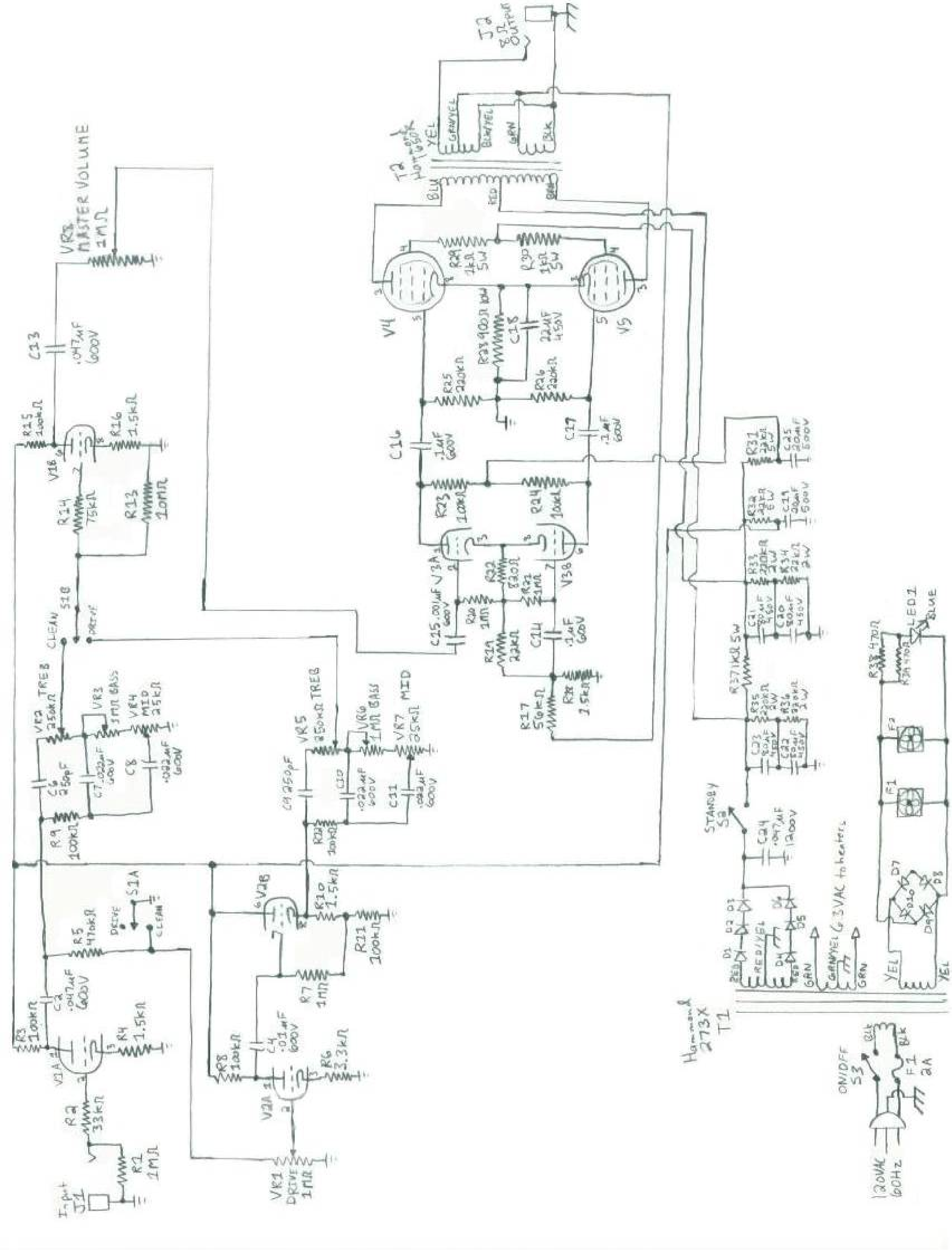
A.11: Winding Diagram for Hammond 1650R Output Transformer



A.12: Output Voltages with 1 KHz, 100mV Peak-to-Peak Input and an 8 Ohm Load (n.b. Measured at Speaker Load; Multiply by 2× for Power Generated by Power Tubes)

Channel and Volume	Peak-to-Peak Output (V)	RMS Output (V)	Output Power (W)
Clean ¼ Max	7.5	2.6	0.8
Clean ½ Max	17.6	5.8	4.2
Clean ¾ Max	31.4	10.4	13.6
Clean Max	29.0	10.8	14.6
Drive ¼ Max	13.3	4.4	2.5
Drive ½ Max	34.7	9.5	11.4
Drive ¾ Max	32.2	11.9	17.7
Drive Max	32.2	12.3	18.8

A.13: Schematic



A.14: Speaker Cabinet Front

A.15: Speaker Cabinet Back

A.16: Speaker Cabinet and Amp

A.17: Amp Front

A.18: Amp Back

A.19: Amp Inside