# Debugging and Testing of a Vacuum Tube Guitar Amplifier

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**Purpose:**

The purpose of this project was to continue my independent study project from last semester. Last semester, I finished up the construction of the amp and also did some measurements. However, it still needed some debugging. I also wanted to do some more tests on the amp, which I was not able to do last semester. For more on the design and construction, see my report from the fall semester of 2004.

**Debugging:**

The main issue that I was still having with my amp was too much gain in the clean channel. This extra gain led to distortion that was very noticeable at high master volume levels. Since the Master Volume only precedes the power amp and phase splitter, the distortion must be occurring in one of these two stages. Using an oscilloscope to probe the outputs of these stages (note: output of the power amp was probed at the speaker output when connected to an 8Ohm resistive load with appropriate power handling capabilities), I found that the distortion was entering the signal directly after the phase splitter. Prof. Errede recommended swapping the phase splitter tube, from a 12AX7 to a 12AT7. The 12AT7 is a lower gain tube that has family curves that are very similar to the 12AX7. Also the 12AT7 is the tube of choice in phase splitters because of its lower gain. The reduction in gain should reduce the distortion somewhat, and hopefully make it better sounding to my ear. After swapping the tube, the distortion was less noticeable both visually on the scope and also musically when played at high volume levels. Although the distortion was reduced, it was still somewhat noticeable. Future ideas are to replace the 12AX7 used in the clean channel of the preamp with a 5751 to reduce the preamp gain. Although the preamp is already running clean, reducing its gain will pass a smaller signal into the phase splitter and hence reduce the distortion added by this stage.

**Testing:**

After making the modifications to reduce the distortion, I wanted to finish up with measurements. Last semester we measured the power supply voltages, power dissipation in the power tubes, noise floor, output waveforms, and frequency response of the amplifier. To add to these measurements, I measured the transfer function of the amplifier from input to output. I used an oscilloscope set up in XY mode and two function generators to accomplish this. One function generator was used to drive the x-axis of the scope directly, and the other was used to drive the input of the amp. The output of the amp was then used to drive the y-axis on the scope. Appendix A.1 gives details on setting up the oscilloscope in X-Y mode for this measurement. Note that the amp was properly terminated in an 8 Ohm resistive load for the duration of the test, and the y-axis probe on the oscilloscope was set to 1 M Ohm input impedance. When setup properly, the scope will trace out the output voltage as a function of the input voltage (the transfer function of the amp).

Once the waveform was displayed properly, I saved each channel to disk and imported them to excel. I was then able to plot out the waveforms, which are shown in A.2 through A.5. From these measurements, we can tell a lot about what is happening in the amp. In A.2, the amp is in its most linear region. This corresponds to a very low master volume setting. Since the amplifier injects minimal distortion in this mode, this is the cleanest setting on the amp. As we move to A.3, we see that a cubic distortion has shown up. This graph corresponds to a slightly higher setting on the master volume knob. The distortion that is observed is a symmetric distortion and will predominantly add a third harmonic component to the output. The cause of this distortion is the family curves (and hence the physics) of the tubes themselves. The nonlinear family curves predict that the tubes will add distortion if not kept in a small region that can be roughly approximated as linear. Turning the master volume up further, we arrive at A.4. Again we see a cubic distortion, but we now see another interesting property. The phase relationship between the input and output waves in this graph is very odd. If the waveform had the same phase relationship at all points, the area enclosed in the graph would be somewhat symmetric across the origin. In fact, if the phase relationship were constant, we could adjust the phase of one of the two function generators, as described in A.1, to make the enclosed area of the graph approximately zero. Here, however, we see that there is more of a phase difference in the third quadrant than there is in the first. This cannot be eliminated, and is a very interesting property. In addition to these two types of distortion, we see that we are just on the verge of entering saturation. This is evident by the second kink in the third quadrant. The figure has just started to asymptote in the horizontal direction. This is due to the negative half cycle devices running into saturation mode. If we now turn the master volume to its maximum position, we arrive at A.5. As with the all distorted figures, there is a cubic distortion. The phase difference is more pronounced here and both output devices have entered saturation mode for the extremes of the figure. The final type of distortion present in the amplifier also arises in this graph. This type of distortion is called crossover distortion, and is seen right around the origin. The flat section of the waveform is where the amp is switching over from one output tube to the other. This takes finite time due to the slew rate of the tubes, so the result is a dead area in the middle of the waveform. This is the most distorted that the output will get, and as we can see it is very much different than the simple linear relationship of A.2.

As was mentioned, the phase difference between quadrants one and three is very odd. I originally thought that this could be due to the power amp set up. Since it is a push-pull amplifier, it has two distinct sections. Ideally these sections are matched, but in reality they are only approximately matched. If this approximate match resulted in a slightly different phase shift for each of the sections, then that might explain the phase difference observed on the Lissajous figure. This phase difference could be in a number of places, so I started by eliminating the easiest first. If a mismatch in the power tubes is adding the phase difference, then swapping them should make the transfer function flip across the origin. The result of this test was no change in the waveform. The next thing to try would be to probe the grids of the power tubes. This would see if the phase splitter added the phase difference or if the power tubes/output transformer added it. However, since feedback is employed around the entire power amp section (phase splitter/power tubes/output transformer), no matter where the phase difference is added, it will be observed everywhere in the system. The only way to truly find the source of this phase difference would be to remove the feedback loop. Therefore, I decided not to proceed with more experimenting on this. One last experiment that I did was to probe the master volume. By probing the input, we should be able to tell if the phase difference is coming from the power amp or the pre amp. However, when we probed this spot, we found another interesting property. The transfer function was really linear, but as the volume was turned up, the waveform developed a very sharp non-linearity. Prof Errede and I thought about why this was happening and the only things we could think of were that the feedback loop was leaking back into the pre amp or that the power amp was affecting the power supply and in turn affecting the preamp. Again to check if the feedback loop is causing this, we would need to remove it. Therefore, we checked the voltages on the power tubes and found that the plate voltage sagged from 400 volts to about 350 volts as the master volume was turned from min to max. At the same time, the cathode voltage increased from 50 volts to 105 volts. Therefore the plate to cathode voltage changed a total of 350 volts to 250 volts during the measurement. This was very shocking. First of all, the large voltage on the cathode means that the tube current is approximately 100 milliamps when the master volume is turned up all the way, due to Ohm’s Law. This means that the power amp tubes are dissipating 25 Watts total (12.5 Watts each). The 100 milliamps observed, means that the cathode resistor is dissipating 10 Watts, which is its power rating. If I plan on using this amp at a high output level for extended periods of time, I will need to change this resistor with one that can handle more power. The sag in plate to cathode voltage is also shocking, and this “browning” explains why the amp sounds really nice when turned up very loud.

**Conclusion:**

With these results, I gained a lot of knowledge as to what is happening inside my amp. I think that I will be done working on this amp for a while, since I think it sounds pretty good now. I will definitely incorporate what I have learned from building/debugging/testing this amp in future amps that I build. I hope to apply the knowledge learned here to make a really good sounding amp that is not right at the verge of destroying some of its components. Also, I would like to use the knowledge learned about the DC power tube voltages to get the benefits of the browning. I also would like to apply the knowledge learned from the Lissajous figures to build a tube amp emulator circuit. This would be an effects pedal that would model what actually happens in a tube amp as it is driven harder and harder. This will not be an easy feat, especially with the phase difference observed here. However, we can see that the emulator will need four distinct types of distortion:

1) Cubic distortion to model the family curves of the tubes
2) Phase difference to model that, which was observed in A.4 and A.5
3) Saturation to model the output devices entering saturation mode
4) Cross over distortion to model the transition between the two output tubes

With these as a starting point, we should be able to emulate 1, 3, and 4 fairly easily. However, 2 will be the biggest challenge. This will require some more thinking and experimenting on the amp to discover the source. Once the source is found, the task of modeling the source will be made easier.

# A.1
# Setting up a scope in XY mode to measure transfer functions of 2 port components.

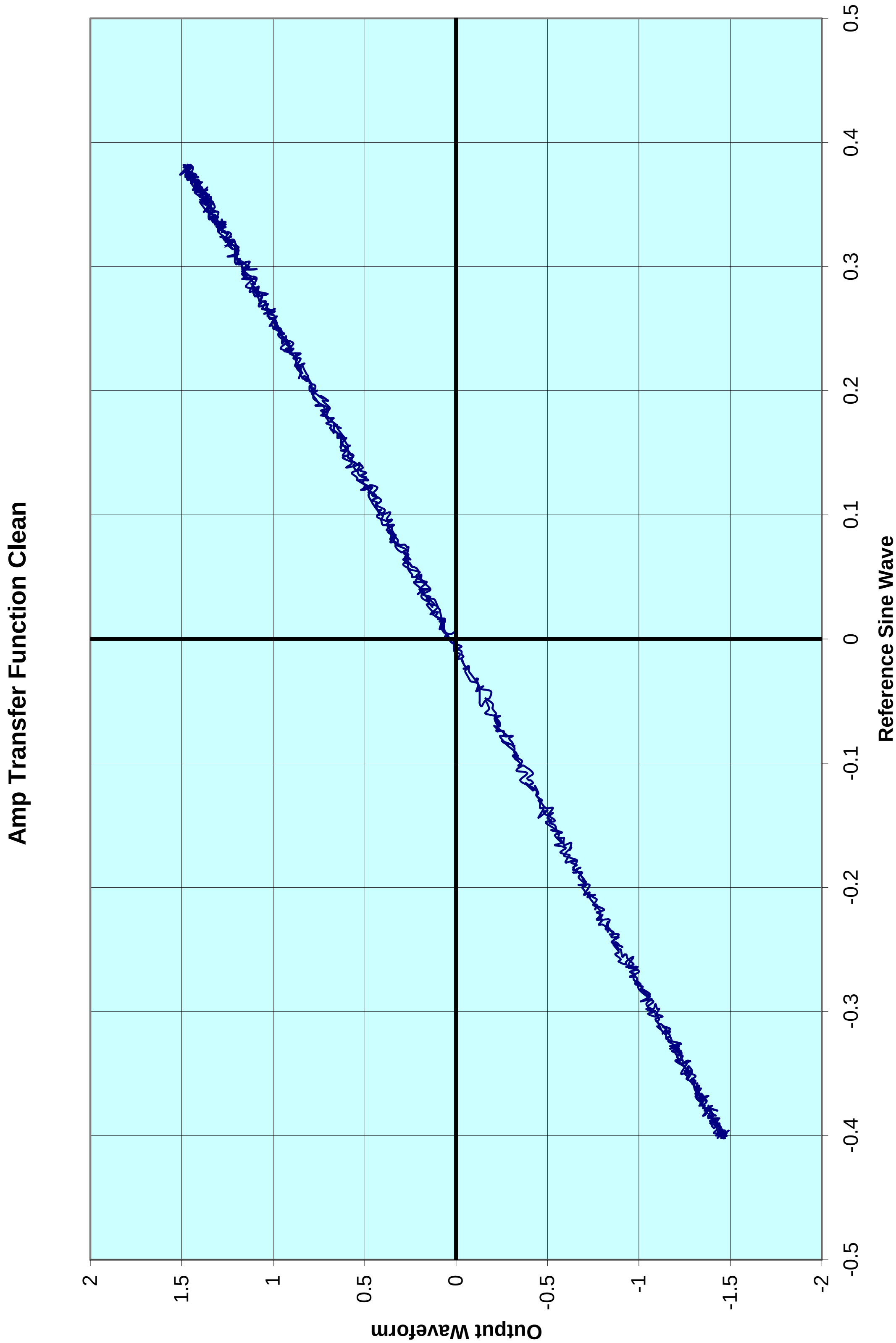
Equipment Needed:

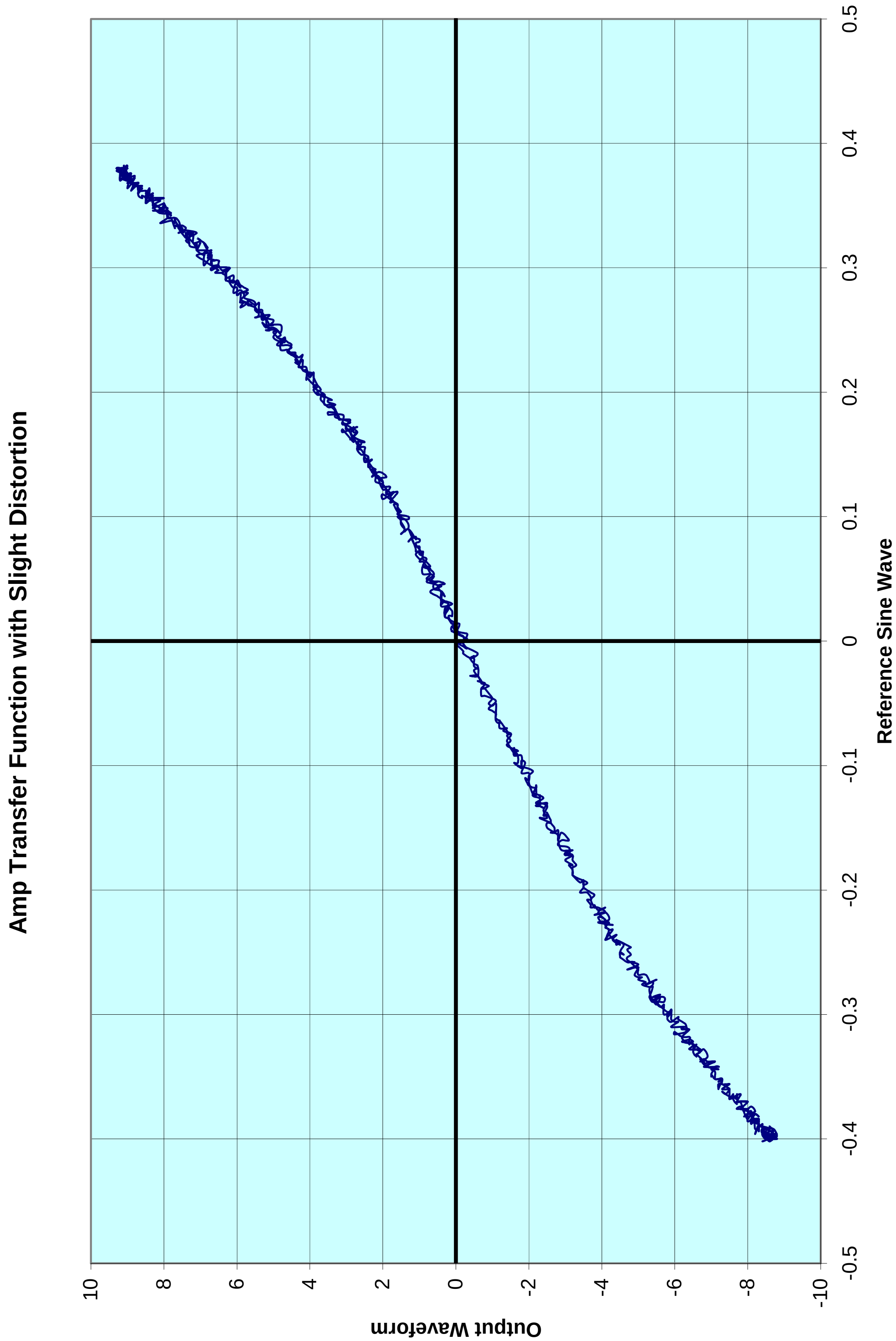
1) 2 Function Generators (Preferably Agilent 33220A's)
2) Tektronix TDS 3012B Oscilloscope (or another scope capable of XY display)
3) Cabling to connect 2 port device to scope and function generators

Procedure:

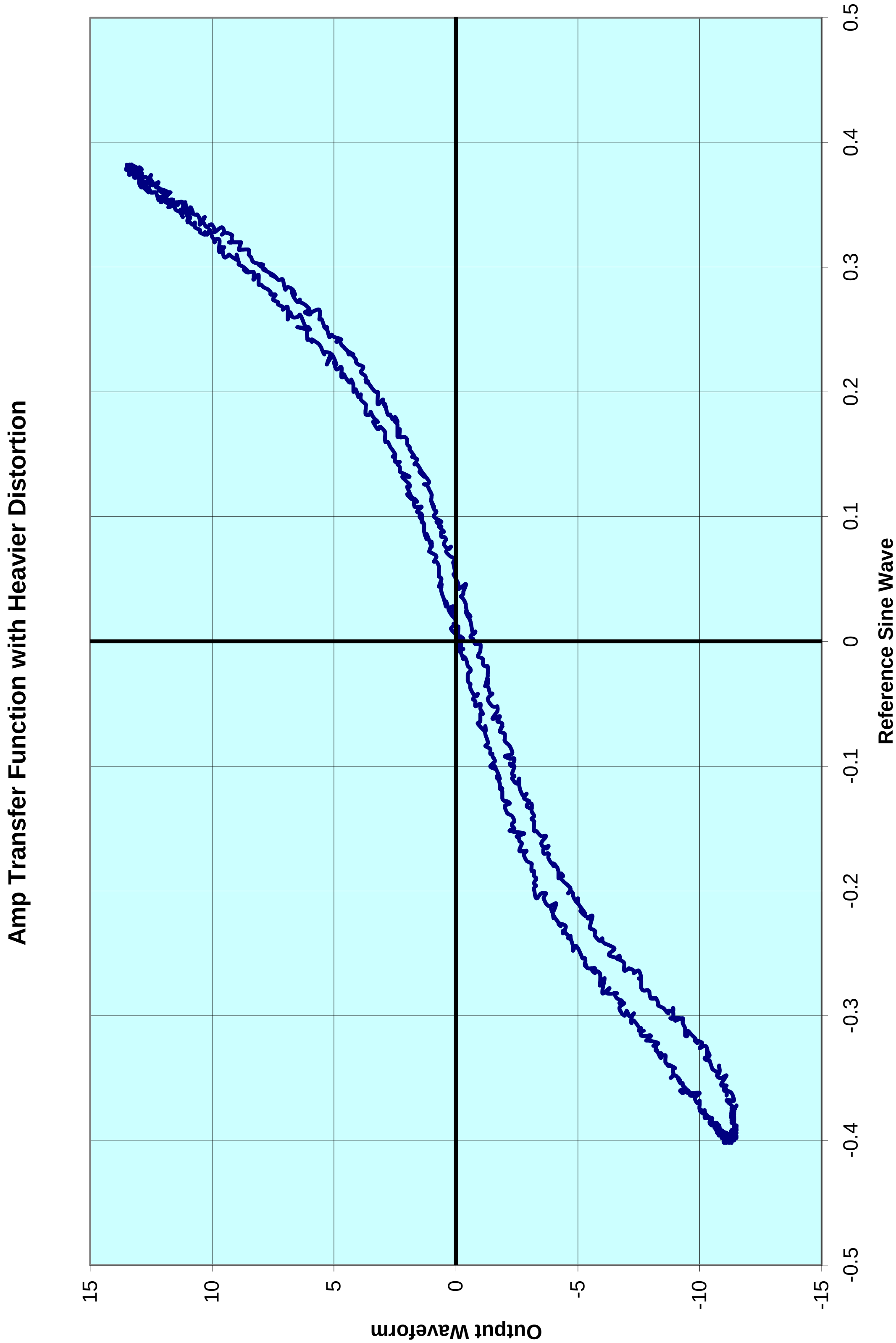
1) Cable one of the function generator outputs to the input of the 2 port component
2) Cable the second function generator to the Ch 1 input of the oscilloscope
3) Cable the output of the 2 port component to the Ch 2 input of the oscilloscope
4) Turn on the function generators
    a. If the 2 port component is active, you may need to decrease the amplitude of the function generator connected to it.
    b. Set both function generators to the same frequency
5) Turn on the oscilloscope
    a. Once the scope is up and running, hit the **DISPLAY** hard button, the **XY DISPLAY Ch1 V Ch2** soft button, and the **Triggered XY** soft button
    b. Make sure both channels are set to the appropriate input impedance
6) Turn on the 2 port component (if applicable)
7) Adjust the scale (both channels and also time) to display the output correctly
    a. Might need to increase the amplitude of the function generators if the output is not visible.
8) Adjust the frequency of one of the function generators slightly to align the phase of the two signals
9) Save the waveform to disk
    a. Insert a floppy disk into the disk drive on the scope
    b. Save Ch 1 Waveform
        i. Hit the **Save/Recall** hard button, **Save Waveform Ch1** soft button (if **Save Waveform Ch2** is displayed, hit the **Ch1** hard button), **To File** soft button, make sure **Spreadsheet File Format** is selected and hit the **Save Ch1 To Selected File** soft button
        ii. This will take a long time to save the waveform, so be patient.
    c. Save Ch 2 Waveform
        i. Hit the **Save/Recall** hard button, **Save Waveform Ch2** soft button (if **Save Waveform Ch1** is displayed, hit the **Ch2** hard button), **To File** soft button, make sure **Spreadsheet File Format** is selected and hit the **Save Ch2 To Selected File** soft button
        ii. This will take a long time to save the waveform, so be patient.
    d. Mark down the label of each file on a sheet of paper for later use. Note that the scope starts saving as file0, file1, etc.
10) Import the data into excel
    a. Load the disk into the computer
    b. Open Excel
    c. Open the Ch1 waveform file
    d. Open the Ch2 waveform file
    e. Copy column B from the Ch2 waveform file and paste it into column C of the Ch1 waveform file
    f. Make a chart using XY scatter and select the appropriate ranges.

**A.2**


Amp Transfer Function Clean
Output Waveform
Reference Sine Wave
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

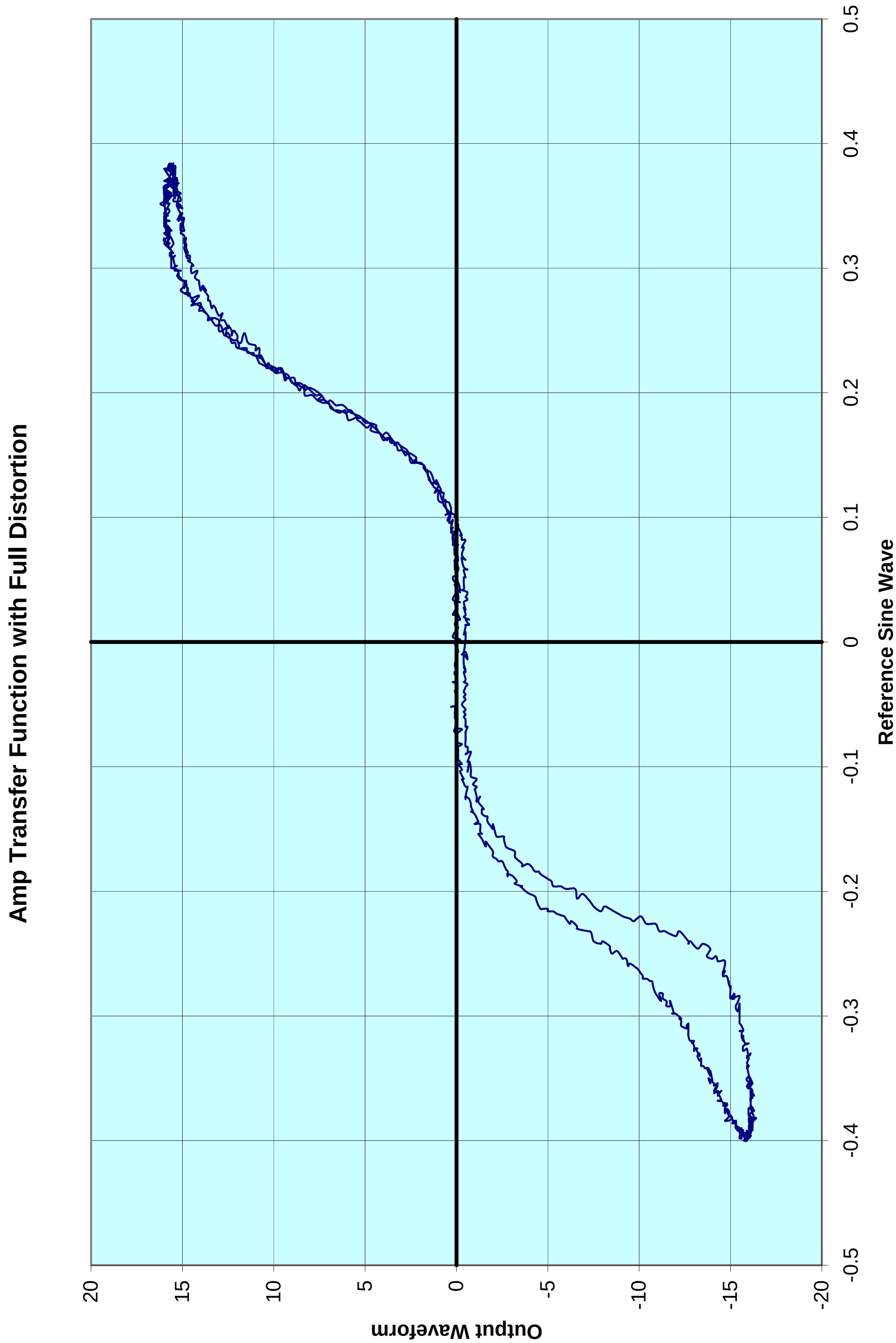

Amp Transfer Function with Slight Distortion
Output Waveform
10
8
6
4
2
0
-2
-4
-6
-8
-10
Reference Sine Wave
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

**A.4**



Amp Transfer Function with Heavier Distortion
Output Waveform
Reference Sine Wave
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

A.5



Amp Transfer Function with Full Distortion
Output Waveform
Reference Sine Wave
20
15
10
5
0
-5
-10
-15
-20
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5