Analog Sound From A Digital Delay

The PT-80 Digital Delay

By Scott Swartz

Introduction

This article will describe a digital delay pedal that is designed to capture the sound and feel of a classic analog delay such as the Ibanez AD-80. I call this creation the PT-80, named after the AD-80 for its sound and the PT2399 delay chip used. Not very creative, I know, but what do you want from an engineer?

I personally own several classic analog delays including an original Ibanez AD-80 and have A/B tested this design against the analog pedals, and the difference in sound is extremely small.

Analog Delay Vs. Digital Delay

In the context of effect pedals, analog delay refers to a circuit utilizing a bucket brigade type chip (BBD) to generate the signal delay.

Using basic terms, BBD chips create a analog representation of the signal by storing an electrical charge that is passed along the “bucket brigade”. The charge is passed at a rate determined by the clock and the magnitude of charge stored at any given instant is an analog value, unlike a digital delay where the amplitude is assigned to a digital value that has discrete steps. At first glance, the BBD therefore has better resolution, but there are a couple of problems. There is degradation of the charge as it passes through the bucket brigade, and more importantly, the process of passing the charge from bucket to bucket creates clocking noise in the signal.

The raw signal leaving the BBD therefore looks like the audio signal, but there are “spikes” in the wave that correspond to the clock frequency. The solution to this problem is remove the spikes with a low pass filter, typically 30 or 36 dB per octave with a –3 dB point of around 3 kHz. This lets enough high frequencies through for a reasonable audio signal, but stops the clock noise. The limited high frequency bandwidth also happens to sound more natural to most people for guitar effects use.

Using basic terms, a digital delay samples the amplitude at a given clock time and assigns it a discrete value, then another discrete value at the next clock time, and so on. After being stored and then turned back into an analog signal via a D/A converter, the raw waveform will have “steps” in it, due to the discrete amplitude storage (the height difference between each step) and the clock frequency (the width of each step). Obviously, the higher the number of bits for amplitude storage and the higher the clock frequency, the smaller the steps added into the waveform, and the easier it will be to filter them out.

If the frequency of the clock is high enough and the amplitude resolution high enough, the steps can be filtered out completely, leaving only the audio. There is a relationship between maximum audio bandwidth, clock frequency, and the filter slope required. For instance, 16 bit CDs use a clock frequency of 44.1 kHz and provide 20 kHz audio bandwidth, therefore a very steep slope filter is required.

So where does that leave us?

-Both digital and BBD technologies will add artifacts to the audio signal.
-Removal of these artifacts is accomplished by low pass filtering in both technologies.
-BBD technology theoretically could have better amplitude resolution. However, the vertical portions of the steps in a digital wave will be sloped and smoothed out by the low pass filtering, and the real world BBD bucket brigade

process will not retain 100% of the amplitude information, so there is probably no clear advantage for one or the other on this point.

Keys to the Analog Delay Sound

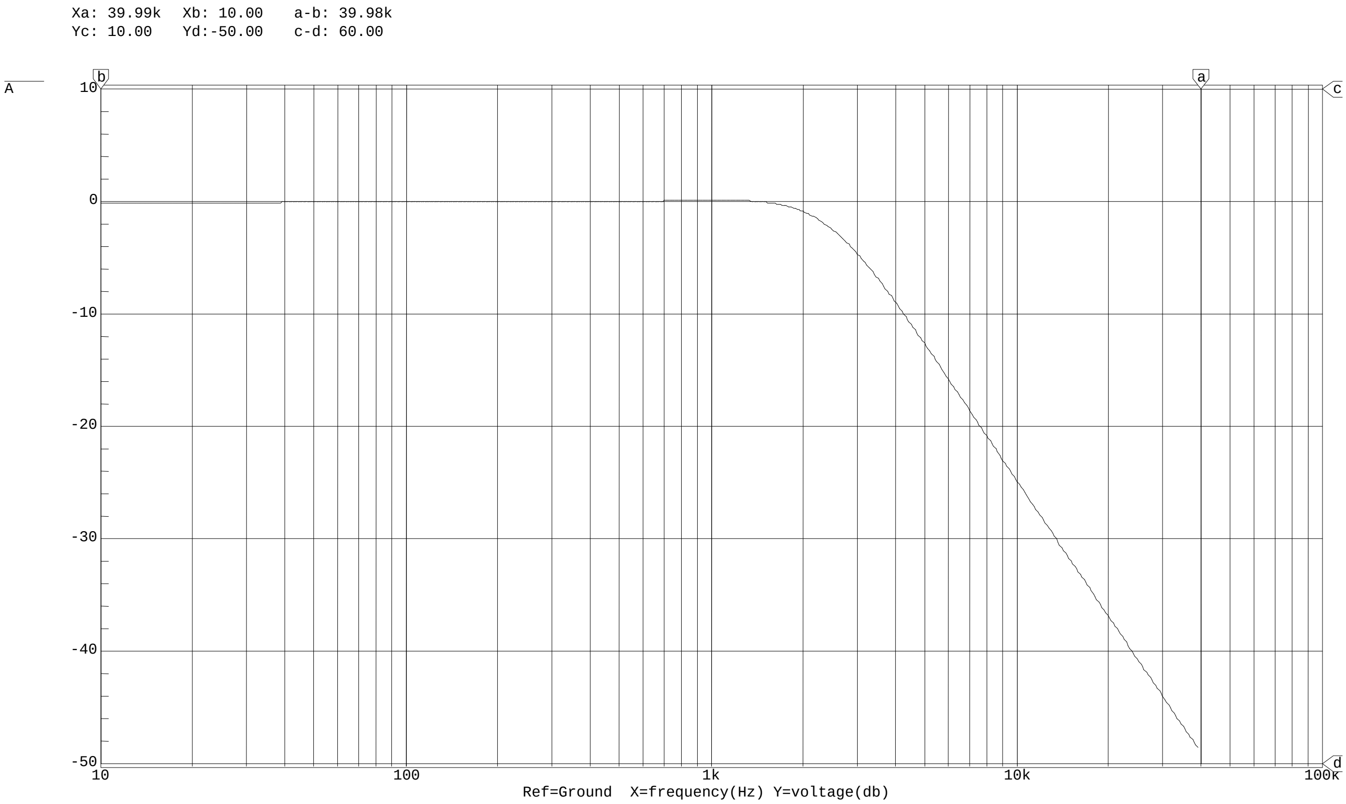
So why do typical digital delays sound terrible for guitar?

The main reason is simple, too much high frequency bandwidth, and the solution is to add filters with the same specs that a BBD circuit requires for proper operation to a digital delay circuit. A filter is typically placed prior to the delay line, called an anti-alias filter filter, and there is filter after the delay line, which we can call a post delay filter.

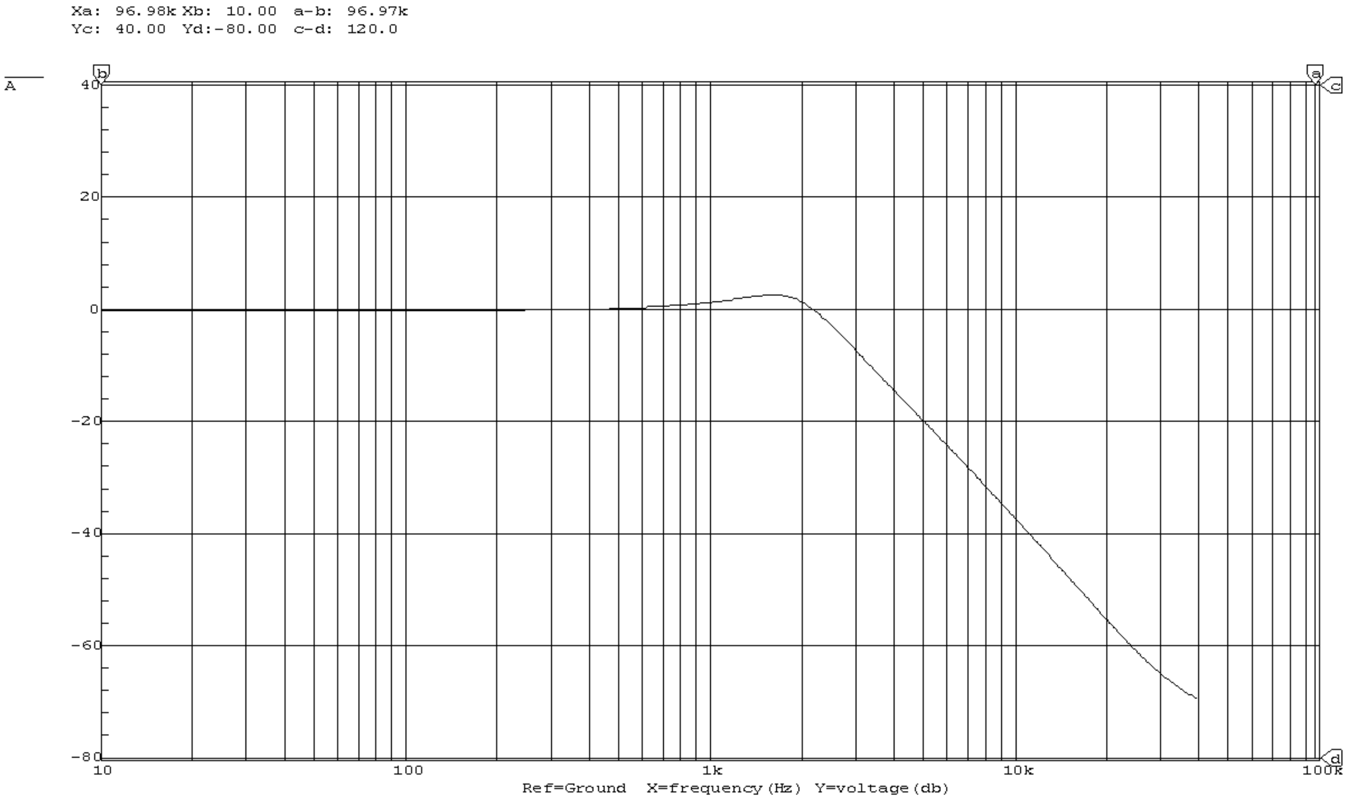
Anti-Alias Filter

The anti-alias filter limits the frequency response to no more than 0.3 times the minimum clock speed, which for a BBD chip will be as low as 10 kHz (a MN3005 will be clocking at 10 kHz when set for 205 millisecond delay). The reason why this filter is required is that the process of modulating the audio signal creates sum and difference harmonics, which need to be filtered out. If we use the example of signal frequency of 3 kHz and clock of 10 kHz, harmonics will be created at 7 kHz (10-3) and 13 kHz (10+3). Therefore, the frequency response of the filter needs to provide as much attenuation at 7 kHz as possible. If you use example frequencies of 5 kHz signal and 10 kHz clock, you can see that the difference harmonic (5 kHz) is the same as the signal frequency, and therefore can't be attenuated without attenuating the signal itself (!), this is the reason for the 0.3 times signal frequency limit.

Here is the response of the anti-alias filter used on the PT-80 design.



So the frequency response at the input to the PT2399 delay chip is limited to about 2 kHz, and higher frequencies are rolled off at 12 dB per octave. This may sound extreme, but this filter performance is typical for analog delays. For comparison, the following is a graph of the anti-alias filter used on the Boss DM-2.

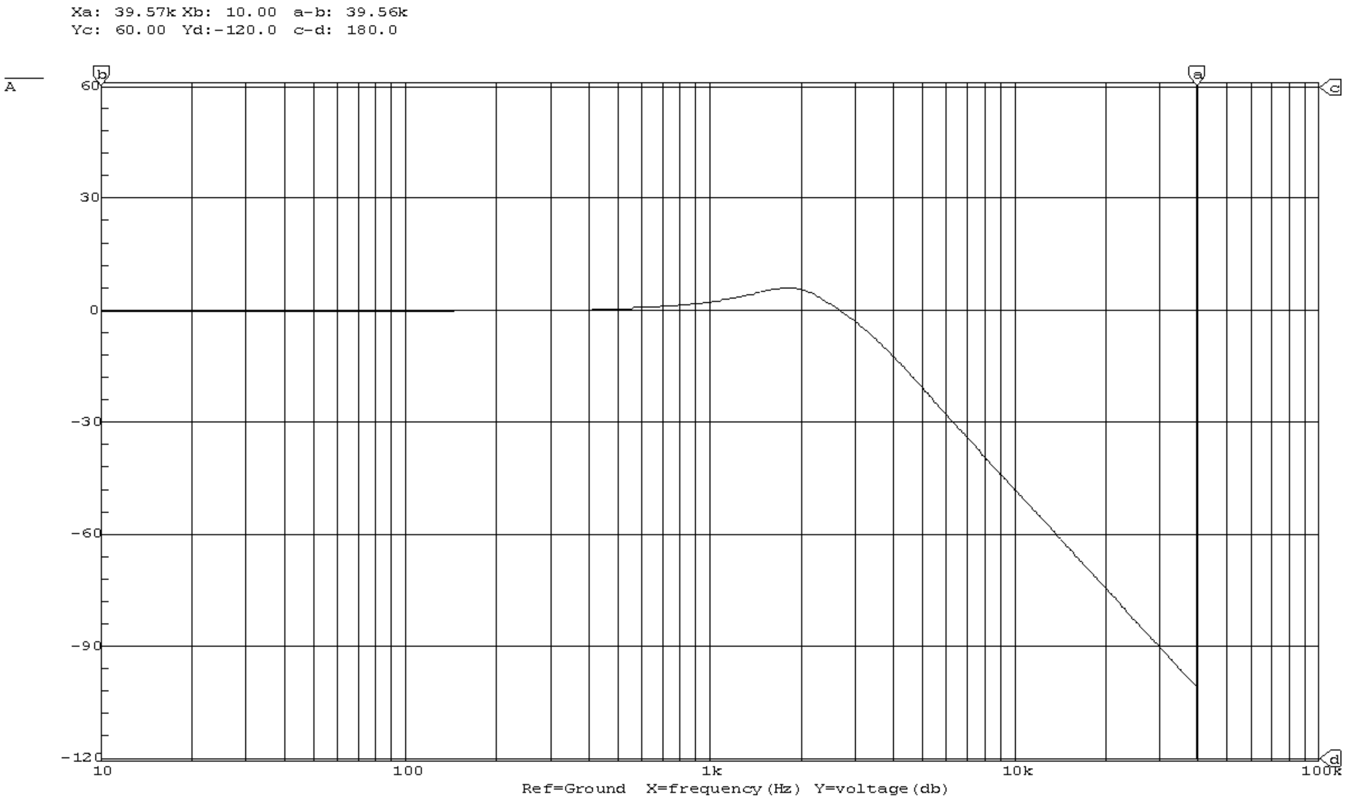


The DM-2 filter is 18 dB per octave and therefore steeper, but the main point is to get the rolloff frequency similar which you can see has been done by comparing the two graphs.

Post Delay Filter

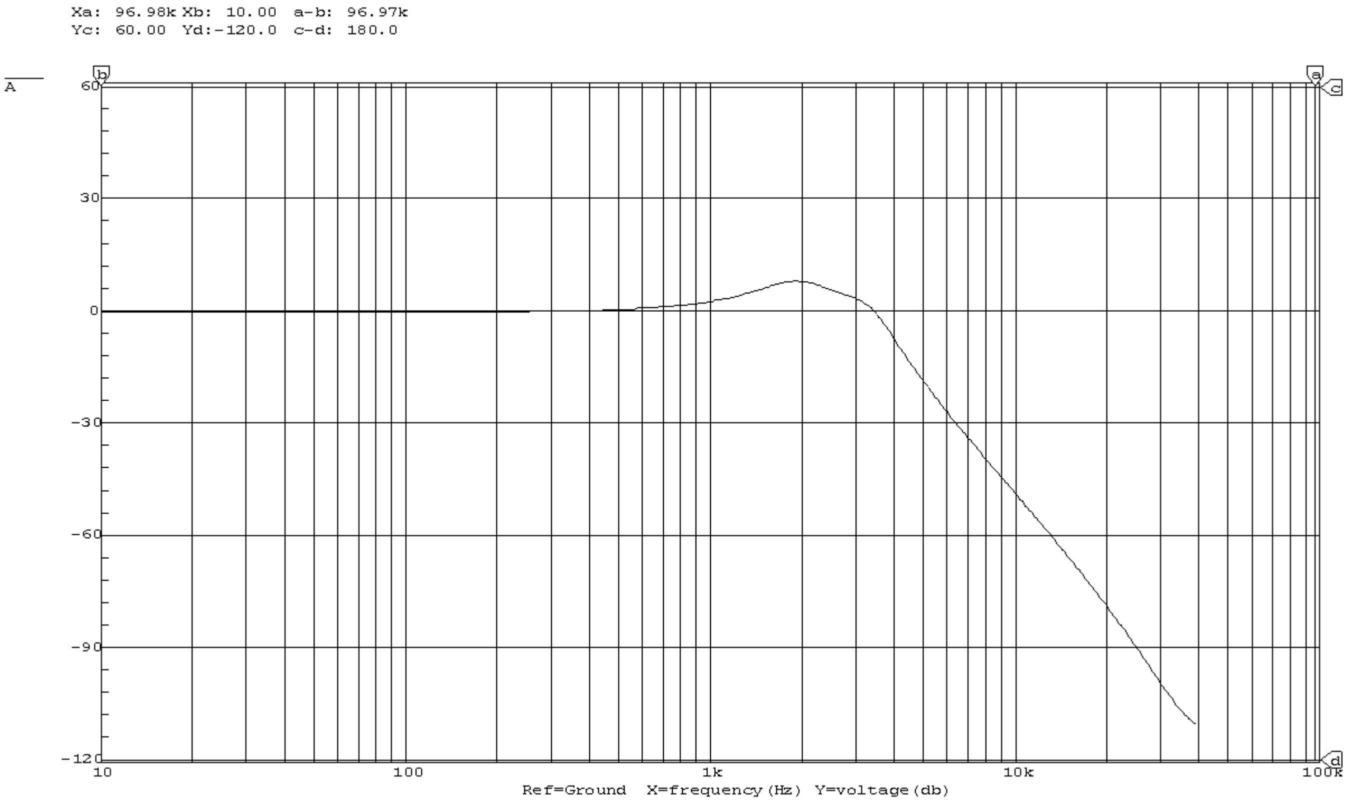
More important to the overall sound is the post delay filter. The PT-80 design uses a 30 dB per octave filter, identical slope to the Boss DM-2, and the frequency response has been made almost identical by careful component selection.

Here is the response of the PT-80 post delay filter.



As visible on the graph, the response falls off very quickly after 2.5 kHz. This rapid rolloff is the main contributor to the “warm” sound that analog delays are known for.

The graph below is the response of the Boss DM-2 post delay filter.



They almost look like the same graph, but they are generated from two different circuits. The PT-80 uses the LPF-2 pins on the PT2399 for 12 dB of the 30 dB rolloff and a transistor circuit to provide the remaining 18 dB per octave rolloff. The Boss DM-2 uses one transistor to generate 18 dB of the rolloff, and another transistor for the other 12 dB of rolloff. The response was modeled using Circuitmaker simulations, and the PT-80 design values were selected to provide nearly identical response.

PT2399 Delay Chip

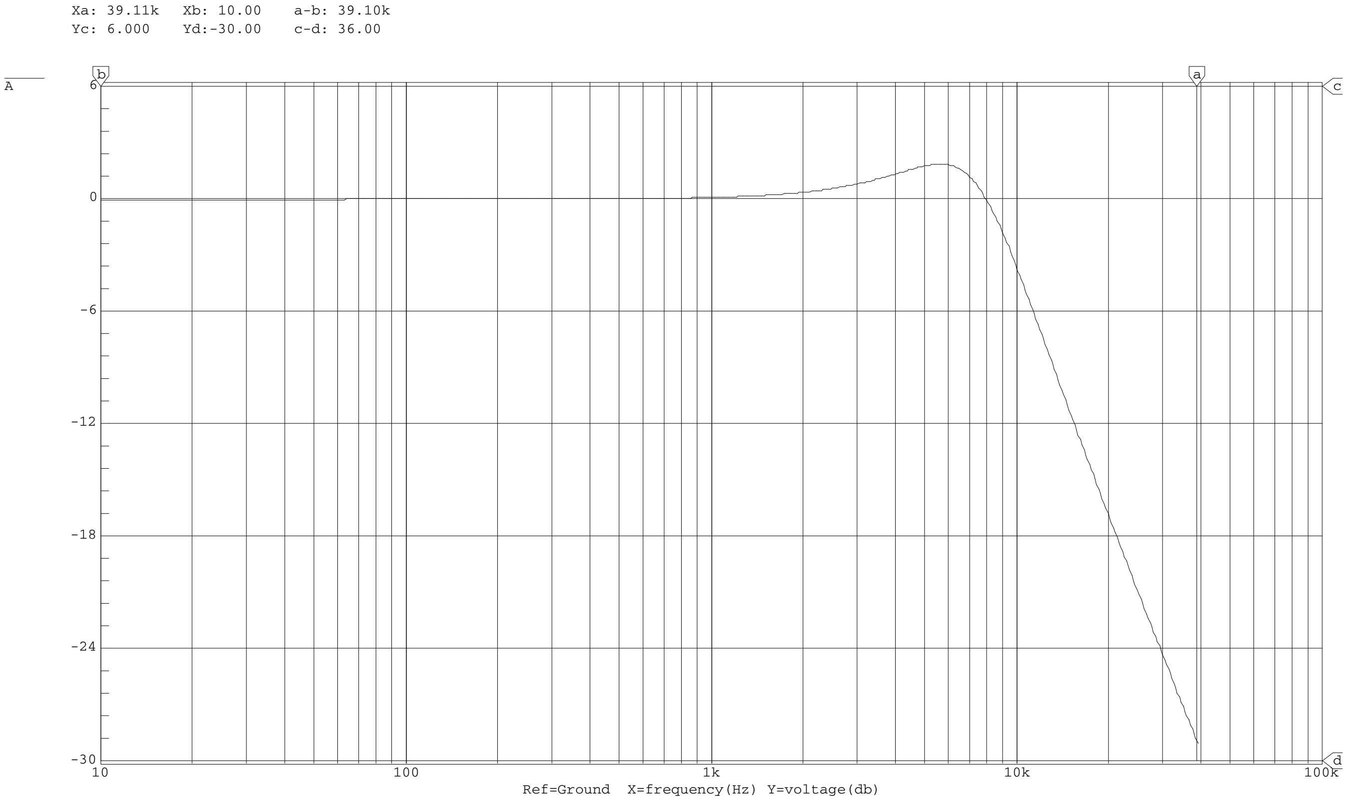
The application note for this chip is not the greatest. The following are some findings about how the chip performs in a real world guitar effect circuit.

-The selection of these PT-80 filter responses (originally selected to simulate the analog delay sound) in conjunction with the PT2399 delay chip turns out to be to be for the best anyway. The intrinsic frequency response of the PT2399 is limited to about 5 kHz after which there is distortion, rolloff, and other digital craziness.

-If a sine wave input of more than about 4 kHz is allowed to processed, it comes out as a triangle wave. This appears to be due to limitations in the chip itself. A guitar signal doesn't have much infomation up in that range, but letting the delay chip process those frequencies will add "grit" to the sound due to the distortion.

-The maximum amplitude signal that can be processed is about 3 volts peak to peak. Signal levels above this are clipped and also have some digital distortion as seen on the scope. Overall, this is enough headroom for guitar level, but certainly not for line level signals.

Here is the response of the anti-alias filter from the app note that uses the 5600 pF and the 560 pF capacitors. The -3 dB point is about 10 kHz, which makes no sense keeping in mind the performance I observed. Who knows?



Companding

The better sounding analog delay pedals, such as the Boss DM-2 and the Ibanez AD-80, incorporate high frequency pre-emphasis and de-emphasis and more importantly an NE570 compander circuit for better noise performance. These functional blocks can also easily be added to a circuit that uses a digital delay line. Companding is required for the BBD circuit to control noise, but even if the digital circuit doesn't require it for noise performance, it can be added to the digital circuit to capture any artifacts created in the analog delay pedals.

Design Summary

The overall design goal of the PT-80 circuit is to take the circuit of a good sounding analog delay, keep everything that may impact the sound quality of the dry signal and as much as possible in the delay signal chain, while changing out the BBD delay line with the Princeton PT2399 digital delay line.

Here is a list of the major functional blocks:

-High frequency pre-emphasis and de-emphasis circuitry from the Ibanez AD-80 (Boss DM-2 is very similar). This is a noise reduction technique and has little or no impact on the sound of the circuit.

-Anti-alias and post delay filters similar to those used on the Boss DM-2 (Ibanez AD-80 is similar)

-NE570 companding from the Ibanez AD-80 using the currently available and functionally equivalent SA571 chip (once again, the Boss DM-2 is very similar)

-Delay repeat circuitry from the Boss DM-2 (the Ibanez AD-80 is almost identical)

-Wet/Dry mix control taken from the Boss DM-2 (the Ibanez AD-80 mixer is harder to adjust, although it can be set for 100% wet output whereas the DM-2 circuit cannot be)

-Finally, a digital delay line using the Princeton PT2399 delay chip

Construction Notes

First, a word about the supply voltage chosen. The schematic shows a +12V regulator, which is the voltage used on the Ibanez AD-80, and will require using a 18 - 24 VDC wall wart for power. I prefer this for the added headroom and cleaner tone of the dry signal at the higher voltage, but the circuit will work fine with a 9 VDC supply. In this case, you would jumper the pads for the 12 VDC regulator input and output, and then you could use a regulated 9 VDC wall wart, such as the Ibanez AC109. Battery operation could then be implemented with a DC power jack that disconnects the battery + when the wall wart plug is inserted, as is commonly done on most effects. Only problem with battery operation is the current draw of the circuit is a stout 35 milliamps, the PT2399 chip alone is about 20 milliamps. You could save a few milliamps by using 10K instead of 1K resistors in the Vref divider, it should work fine, and maybe a TL062 opamp, that will get the current draw down to about 27 milliamps.

The layout is designed to fit in the typical Hammond 1590BB box, which is 3.7 x 4.7 x 1.1 inches, with the PC board size being 2.5 x 3.2 inches. The intended mounting scheme is to mount the board on ½ inch tall standoffs with the pots mounting underneath the board. It could also be mounted on washers or short standoffs by moving the footswitch and pots far enough apart to allow the board to fit between, although in that case there may not be enough room for a battery if you go with 9 volt power.

The PCB layout is designed to accommodate metallized polyester 1 uF coupling capacitors, although axial electrolytic or tantalum caps could be used (if correct polarity is observed). Other smaller caps are laid out with 0.3 inch spacing between pads, which should allow for various brands of caps to be used. Resistors have 0.4 inch pad spacing and are fine for use with the typical ¼ watt resistors.

The Sound

OK, so the big question.

Does it sound like a classic analog delay?

It comes VERY close to the sound of my original Ibanez AD-80. The difference is barely audible, its like comparing the AD-80 to a Boss DM-2 to a Ibanez CD-10 to a EH Memory Man. They all sound a little different.

Keeping in mind I am referring to very small differences, I would say the PT-80 repeats frequency response is identical, but the repeats seem to be a little crisper, ie a more defined attack. Part of the difference could be the metallized polyester coupling caps I used, electros will soften the sound somewhat.

The sound is worlds apart from the overbearing sound of a typical digital delay like the Boss DD-3 or a multi effects unit (Digitech, Lexicon, etc), where the repeats are so distinct they interefere with the dry signal. The PT-80 gives the “atmospheric” quality of an analog delay.

With the 50K delay time pot, the delay can be adjusted much longer than a typical BBD delay, although the repeats are a little grainy at the longest delay times. A 25K delay pot gives a range almost identical to a BBD delay and makes adjustment of delay time a little easier.

You are now armed with the schematic, PCB layout, and technical background required to build a great sounding delay pedal.

Have Fun,

Scott Swartz