Analysis of a Modified

Boss DS-1 Distortion Pedal

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ABSTRACT
Guitar players are increasingly modifying (or paying someone else to modify) inexpensive mass-produced guitar pedals into boutique units. The Keeley modification of the Boss DS-1 is a prime example. In this paper, we compare the measured and perceived performance of a Boss DS-1 before and after applying the Keeley All-Seeing-Eye and Ultra mods. This paper sheds light on psychoacoustics, signal processing, and guitar recording techniques in relation to low fidelity guitar distortion pedals.

1. CLIPPING
The Boss DS-1 is a hard-clipping signal processor. A voltage representing the audio wave of the guitar is input to the DS-1. The pedal clips off the tops and bottoms of the waves and outputs the result. Figure 1 graphically shows hard and soft clipping. One can easily see from a quick glance at figure 1 that one can clip a signal in many ways. One could change the threshold voltage where clipping begins so that more or less of the wave is clipped. One could keep a constant clipping threshold voltage, but change the amplitude of the input wave to increase or decrease how much
clipping occurs. One can also change how ‘hard’ or ‘soft’ the clipping is.

Out-of-the-box, the DS-1 uses a simple diode clipping circuit to achieve hard clipping [2]. A simplified version of the clipping circuit is shown in figure 2. Here we see an op-amp that amplifies the input signal and the diodes that clip the amplified signal. The diodes set a clipping threshold of about 0.6 V. By controlling how much the op-amp amplifies the input signal, the user can increase or decrease how much of the wave is clipped. If the wave is clipped hard enough, it will look like a square wave. The resulting square wave output will contain the input’s fundamental, but also add odd harmonics to it.

An easy way to compare diodes is by looking at current versus voltage plots. Figure 3 on the next page shows the current-voltage characteristic of a diode we removed from the DS-1, of a light emitting diode (LED) that we used to modify the DS-1, and of the LED and original DS-1 diode in series. One can see that the current-voltage plots vary in two major ways. First, at what voltage does the diode begin to conduct current? This voltage sets the threshold clipping voltage. Second, how steep is the curve? A steeper curve means more resistance to an output-voltage increase, and therefore harder clipping. One can relate these plots to our movement-in-a-pool analogy by keeping in mind that power is equal to voltage times current. The electrical power the op-amp puts out is like the physical power you exert in the pool. The final output voltage is how fast you’re able to move.

2. THE KEELEY MODIFICATIONS

According to Keeley [3], the modded DS-1 provides the “finest in Marshall-amp tone-in-a-box.” Keeley touts the modification as the perfect way to get an AC/DC, Van Halen, or Steve Vai sound. The pedal increases distortion range, improves bass response, and increases second order harmonics to provide the user with “tube-like qualities.” A modified DS-1 is available from Keeley for $130 or for around $55 one can buy a DS-1 and modify it based on Internet instructions [4].
The Keeley modifications replace several resistors and capacitors in order to improve frequency response and fidelity. A discussion of each part change is beyond the scope of our discussion, but we encourage the reader to examine these changes and convince him or herself of their expected effect.

To increase second order harmonics and tube-like qualities, Keeley changes the diodes used in the DS-1’s clipping stage. While these changes are small, they fundamentally alter the pedal’s performance. Figure 1 showed a simplified version of the pre-modification clipping stage. Figure 4 shows a simplified schematic of the clipping stage after the Ultra mod. The Ultra mod replaces one of the diodes with an LED. This change results in asymmetric clipping. One side of the wave is still hard-clipped at around 0.6 V as before. The other side of the wave is now being clipped by the LED. Referring back to the LED’s current-voltage characteristic in figure 3, we can see that the LED will clip at about 1.7 V and will clip softer than the other diode. Introducing softer-clipping at a higher clipping-threshold on one side of the wave form should increase distortion range and increase second order harmonics.

Figure 5 shows the clipping stage after the All-Seeing-Eye mod. Here, one of the diodes has been replaced with an LED. In addition, a second LED has been added in series with the remaining diode. Again, we should refer to the current-voltage characteristic in figure 3. The LED has a threshold clipping-voltage of about 1.7 V and clips softer than one diode alone. The LED and diode in series have a threshold clipping-voltage of about 2.3 V and clips even softer than an LED. This change results in asymmetric clipping. The All-Seeing-Eye mod also clips at a higher threshold voltage than the original DS-1 or the Ultra mod. When clipping does occur, the All-Seeing-Eye mod clips softer than either the original DS-1 or Ultra mod. The
result is an increase in distortion range and second order harmonics.

![Simplified All-Seeing-Eye Clipping Stage](image)

Figure 5: Simplified All-Seeing-Eye Clipping Stage

One should note that the Keeley webpage claims that the modifications will increase tube-like qualities. “Tube-like qualities” is a vague statement. Actual tubes achieve distortion through tube saturation. For the purposes of this paper, we will not discuss tube saturation at length, but we will make a few key points. First, tube saturation generally sounds different from diode clipping because the circuits operate differently. Second, it is tough to generalize what tube distortion sounds like because different tubes in different circuits create different sounding distortions. Third, there are a couple of generalizations that we can make about tubes. Tube distortion tends to have very high distortion range. This is because tube designs are generally created to minimize distortion when the tubes operate at low volumes. As a result, when saturation is achieved it will provide a full range from subtle to over-the-top fuzz. Also, tubes do not hard clip the signal. The result is more second-order harmonics than most solid-state distortion circuits. We can easily measure if the Keeley modifications increase second-order harmonics and distortion range. However, it is far more difficult to verify tube replication than tube qualities.

3. ELECTRICAL ANALYSIS

To analyze the effectiveness of the Keeley modifications we purchased an unmodified Boss DS-1. We then modified the pedal using instructions from the Internet. The modified pedal has a switch that allows the user to choose either the All-Seeing-Eye or the Ultra mod. We performed an electrical analysis of the pedal before and after the modifications.

![Guitar Impedance Model](image)

Figure 6: Guitar Impedance Model

Our measurements assumed that a player would plug a single-coil passive-pickup guitar directly into the DS-1. To model the guitar’s impedance we built the circuit shown in figure 6 [5]. We attached our test signal to Vin and attached Vout to the pedal’s input. The transformer models the inductance of the guitar pickup. The resistor and capacitor model the impedance of the cable. Using this setup, we ran several tests using D-Scope to check Keeley’s claims.

First, we measured the pedal’s frequency response at various tone and distortion settings. Next, we measured harmonic distortion at a range of frequencies from 80 Hz to 8 kHz. Last, we measured the percentage distortion across the guitar’s frequency band. We took all of these measurements with an input of 100 mV RMS, which is the low end of the average guitar’s output voltage [6]. Note that the before and after measurements were done on the same pedal. In doing so, we ensure that variations in the before and after data are the result of the modifications to the pedal and not major electronic variations between two pedals.

Our findings supported Keeley’s claims. We found an improvement in frequency response and an increase in distortion range. Figure 7 on the next page shows the frequency response of the pedal with all knobs centered. One can see that after the modifications, the frequency response is essentially flat with a slight boost in the bass. This is in keeping with Keeley’s claims of better frequency response and increased bass. Bear in mind that electric guitar primarily exists in the 80 to 8000 Hz range, so the low and high-end roll off is occurring outside of the guitar’s primary frequency band.
Figures 8, 9, and 10 show percentage distortion as a function of frequency. Each figure compares low-gain with high-gain distortion. In all measurements, the tone knob is centered and the level knob is maxed. One can see that the modifications do increase distortion range. Pre-modification, low end distortion increases from approximately 10% to about 20%. The mid-range distortion peak jumps from 45% to 55%. Compare this to the All-Seeing-Eye mod. While the overall distortion is less than pre-modification, the distortion at 100 Hz now jumps from less than 10% to 33%. Meanwhile the mid-range distortion peak goes from 35% to 43%. The Ultra mod perform similarly. At 100 Hz, distortion goes from 15% to 35%. The mid-range peak jumps from 38% to 43%. So what do all these numbers mean? For starters, at low frequencies, the modifications allow the user to play with lower or higher level distortion than the unmodified DS-1. There is an unquestionable increase in distortion range. We also see that the shape of the distortion curve changes. It is less dominated by the huge mid-range peak—lower frequencies are allowed to play a bigger role in distortion. If we relate these changes to perception, we would probably expect the modified pedal to sound fuzzier than the more buzzy pre-modification distortion. We will discuss how users actually perceived the sound change later on.
We also found an increase in second order harmonics. We looked at fast Fourier transforms (FFTs) for low, middle, and high gain at 80, 100, 250, 500, 800, 1000, 1250, 5000, and 8000 Hz. The tone knob was centered and the level knob was maxed in all measurements. To illustrate our findings, we present the FFTs for low and high gain at 800 Hz. Each graph shows the FFT and the corresponding output wave. In figure 11, one can see that at the lowest distortion level, the DS-1 does produce even harmonics. However, odd harmonics dominate. The third and fifth harmonics are both louder than the second and fourth. Compare this to the All-Seeing-Eye and Ultra mods (figures 12 and 13) where all of the even harmonics shown are louder than the next (odd) harmonic.

Next, let’s look at the FFTs when the gain is turned all the way up. As expected, figure 14 shows that pre-modification DS-1 distortion is dominated by odd harmonics. Also, note that odd harmonics became more dominant when the gain was increased. We would expect that because higher gain means harder clipping. In fact, with the gain maxed, the All-Seeing-Eye and Ultra mods are also dominated by the odd harmonics (figures 15 and 16). However, the even harmonics are more strongly present after the modifications than they were before.
Figure 11: Pre-Modification FFT and Output Wave at Low Gain (800 Hz Input)

Figure 12: All-Seeing-Eye FFT and Output Wave at Low Gain (800 Hz Input)
Figure 13: Ultra FFT and Output Wave at Low Gain (800 Hz Input)

Figure 14: Pre-Modification FFT and Output Wave at High Gain (800 Hz Input)
Figure 15: All-Seeing-Eye FFT and Output Wave at High Gain (800 Hz Input)

Figure 16: Ultra FFT and Output Wave at High Gain (800 Hz Input)
4. HUMAN ANALYSIS

In the end, the real measure of the Keeley modifications is how they sound. Perception of improvement or degradation of the pedal’s performance is inherently subjective. We attempted to evaluate the pedal’s perceived sound by letting several guitar players take the pedal home for a couple of days and try it out. We then had the players describe how the pedal sounded. Players ranged from semi-professional to full-time guitarists. Our guitarists also play a variety of styles from blues/Americana to metal. About half of the guitarists primarily play rhythm. The other half play lead. After the pedal was modified, we allowed players to take the pedal home again. When they returned the pedal, they described how it sounded and how they thought the pedal had changed since the last time they played it. One should note that we did not let players compare a modified and unmodified pedal side by side. If a guitarist chooses to have a pedal modified, then the player ordinarily plays the pedal pre-modification, sends it to be modified, and then plays it post-modification. We also didn’t tell the players how the modifications were supposed to change the sound of the pedal. They were only told that the modifications were intended to be improvements. In this way we may have led them to believe that an improvement had been made, but did not lead them to use specific terms or phrases to describe the change.

4.1. Pre-Modification

Players were universally impressed by how much bang-for-the-buck the DS-1 provides. In general, players felt that the pedal offered an appropriate amount of feedback (not too much or too little), that the distortion was powerful, high frequencies sounded good, and single notes sounded good. Usual complaints included muddy sound in the low frequencies, lack of string dynamics, and lack of distortion range. One player described the pedal as both good and bad because it is abrasive with no sense of subtlety. He continued to say that the pedal was fantastic for grunge or the reckless hard-attack player, but if you wanted to play with any kind of dynamics or subtlety then the DS-1 is a terrible choice.

4.2. Post-Modification

Most players thought the modification was an improvement. All of the players were drawn to the All-Seeing-Eye mod over the Ultra mod. Every player commented on the improvement in frequency response, particularly in the low-end. Guitarists also found that they were no longer constantly tweaking the tone knob when they used the pedal. Most players pointed out improved string dynamics and superior distortion range. Guitarists found the distortion to be fuzzier and smoother than it had been before. Half of the players said that the mods were an improvement for most styles of music, but for some types of hard rock the DS-1 sounded better before the modification. One player said that palm-muting sounded better before the modification. On the whole, the more a guitarist played hard rock the more likely the player was to like the original DS-1.

Players almost universally identified changes to the pedal’s performance that we identified in our electrical analysis. However, we noticed that none of the players described the pedal as sounding tube-like. When asked explicitly, all players said that the pedal still sounded solid-state. One player said that the modifications created more tube-like qualities, but that overall the distortion still didn’t sound like a tube. We also noticed that none of the players compared the pedal to a particular amp or band. When we told them the pedal was supposed to create “Marshall-in-a-box” sound like AC/DC or Van Halen, all players said that the pedal did not sound like AC/DC or Van Halen.

5. CONCLUSIONS

We found that the Keeley modifications improved overall frequency response, bass response, distortion range, and increased second order harmonics. We verified these improvements by making electronic measurements as well as by collecting comments from guitar players. However, based on human response, we found that the Keeley modifications failed to produce AC/DC or Van Halen sound and failed to accurately replicate tube distortion.

We found that while guitar pedals tend to be sold by comparing their sound to existing amps or musicians, guitar players do not talk about pedals using the same terminology. On some level, describing a guitar pedal is difficult because it is inherently difficult to describe how something sounds. Comparisons to high-end players and gear make sense if the goal is to sell pedals. We do credit Keeley for giving a technical description of their pedal, unlike many of their competitors [7]. However, there is room for improvement in how we as a community talk about guitar pedals. We found that all of the guitarists we worked with were able to
understand an elementary description of clipping. Most of the guitarists had little to no electronics knowledge. A couple of them didn’t know what diodes were before we explained the clipping circuit. The point is guitar players can understand the fundamentals of how their equipment works and are more likely to get the sounds they want from their gear if they do. In addition, understanding why different pieces of gear sound different is more useful than saying a certain amplifier or pedal sounds like a certain musician. Gear helps musicians get their individual sound, but guitar tone is heavily influenced by how the guitarist plays. There are lots of Van Halen-tone pedals out there, but not many records with Van Halen tone.

There will always be players who want to buy pedals that will make them sound like their favorite player and don’t want to understand any of the technicalities of their own gear or their favorite player’s gear. Companies will continue to sell pedals that provide players with “perfect” tone. However, we should make an effort to think about pedals in a more realistic and meaningful way. We should acknowledge that higher fidelity or more second order harmonics doesn’t necessarily mean better. It means different. We should try to talk about pedals in terms of their defining characteristics instead of ascribing unachievable qualities to them. Understanding and realistic language will help individual players select the right pedals for them, not the right pedals. More informed use of pedals by individual players means better individual sound and ultimately better sounding music.

6. ACKNOWLEDGEMENTS

We would like to thank Brad Avenson for allowing us access to Avenson Audio’s workshop and test equipment as we investigated the DS-1 and the Keeley modifications.

7. REFERENCES


