# Distortion Pedals

## How can the circuitry inside a distortion pedal be adapted to meet the requirements of specific genres of music and can it emulate the sound of valve amplifier?

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# Introduction

## What does this research project aim to answer?

Bartlett B. (Perfect FX Set-ups, 2005) wrote an article aimed at guitar players, which defined "The essential effects for the essential music genres." The “essential genres” were defined as Metal, Blues, and Alternative Rock. He suggested that there are certain distortion pedals that every guitar player must have when playing these genres: a 'BOSS MT-2 for Metal, a 'Crowther Hotcake Bluesberry' for Blues and a 'Pro Co Rat II' for Alt. Rock.

This research project will address the ways in which the specific guitar sounds of different genres of music can be created through the use of a distortion pedal. The main focus of the project will analyze how altering the type of diodes in the clipping circuit of a distortion pedal can tailor the sound to:

1. Emulate the sound of the three key genres of music stated by Bartlett B. (Perfect FX Set-ups, 2005)
2. Emulate the much sought after sound of the valve amplifier.

The three genres of music will be defined and their history and sound will be analyzed in order to discover in each case, the perfect sound for the genre. Suggestions will also be made for other distortion pedal setups that should be considered when trying to achieve any given distortion sound.

## What brought about distortion?

> "In the past guitarists often found that they could not be heard over the sound of drums and brass instruments. Microphones and amplifiers had been around for a while, so the obvious thing to do was mike up the acoustic guitar. This worked to some extent but often caused problems with feedback, it also meant the guitarist had to sit right in front of the microphone and could not move around. A well-known guitarist called Les Paul devised a way of electrifying his guitar with a needle from an old gramophone plugged into an old radio.
>
> Perkins ("The Guitar", online)

This did manage to amplify his guitar but it still caused feedback problems due to the hollow body of the acoustic guitar. To get around this problem Les Paul invented a guitar that had a solid body so that it would not generate feedback.

> In the sixties innovative guitarists including Eric Clapton, Jeff Beck and Alvin Lee found that by turning a valve amp up full they could make it distort and a whole new sound was created. Unfortunately this sound could not be achieved at low volumes so the distortion pedal was created. This way the guitarist can get distortion without deafening themselves.
>
> Perkins ("The Guitar", online)

**Why are the characteristics of distortion important to the guitarist?**

Different guitarists prefer different types of distortion. This judgment is usually based on the type of music they play. Some distortion can add perceived warmth to a guitar sound whilst still preserving many of the subtleties of the guitarists playing. This type of distortion is often referred to as being "musical" (for reasons that will be discussed later). It has, however, become apparent that not every genre requires this sound.

Wikipedia (Grunge Music, 2005, online) suggests that "Grunge music [Alt. Rock] is generally characterized by dirty guitars, strong riffs.......[and] dissonant harmonies" suggesting that "musical" distortion is not required or desired. "The lyrics in Grunge music are typically angst-filled — anger, frustration, ennui, sadness, fear, and depression are often explored in grunge songs," (Grunge Music, 2005, online) suggesting that "musical" distortion would take away from the meaning of the genre.

As a contrast to the sound of Alt. Rock, Cross (Learn to Play Like B.B. King n.d. online) suggests some important aspects about the playing of one of the pioneers of Blues music;

> "One of the really great things about B.B. King's [pioneer of Blues] music is its simplicity. As cool as his guitar playing sounds, the truth is, King's basic solo style is pretty easy to learn. Besides the actual notes that B.B. King plays ........ there are a few major concepts that define B.B. King's guitar work - his phrasing, and his very unique vibrato."

To retain the sense of phrasing and simplicity described by Cross, a guitarist needs to use dynamics, which is something that heavy distortion (a feature of Alt. Rock) limits due to its compression characteristics.  It is clear from this example that one type of distortion would not be suitable for both Blues, Alt. Rock or indeed Metal.

# The Sounds

## The Blues Sound

As mentioned above, one of the key aspects of blues music is its simplicity. Blues music originated from West African slaves in South America.

> “Black slaves developed a "call and response" way of singing to give rhythm to the drudgery of their servitude. These "field hollers" served as a basis of all blues music that was to follow.”
> (“Blues music,” online)

When the electric guitar was invented by Les Paul, Blues music was able to take a step forward.

> “Because the electric guitar was amplified, guitarists found they could use thinner strings. Artists such as B.B. King found they could bend the strings to add expression to their playing. Chuck Berry took this one stage further by bending double strings in his unique rock 'n' roll style.”
> Perkins
> (“The Guitar”, online)

Through listening to records by B.B. King one can hear the expression (through use of dynamics) that is instilled in his playing. He will play some passages so quietly that they almost fade out completely where in other passages he is playing so aggressively that you can hear the amplifier beginning to clip.

A Blues guitar sound would therefore benefit from being very dynamic. It should also be a close emulation of the traditional sound of a valve as that was the technology that was available to the pioneers of the genre. Not too much distortion is required but just enough to add expression into the player's technique when he plays more aggressively.

## The Heavy Metal Sound

> "The essential sonic element in heavy metal is power, expressed as sheer volume. Loudness is meant to overwhelm, to sweep the listener into the sound, and then to lend the listener the sense of power that the sound provides. Injunctions such as "Crank it up," "turn it up," and "blow your speakers" fill the lyrics of heavy metal songs."
> (Weinstein, 1991, P23)

Heavy metal was introduced to the music scene around the early 70's and so benefited from already having a great deal of guitar technology already available to it. The idea of driving a valve amplifier had already been introduced by rock guitarists so this just had to be taken to the next level.

> "At concerts the stage is loaded with stacks of amplifiers so that the decibel level of the instruments can be raised to the limit."
> (Weinstein, 1991, P23)

Through listening to songs by artists such as "Slayer" and "Metallica" one can hear that the guitars are heavily distorted. The distortion also contains a lot of high frequencies allowing it to cut through the drums and bass for solos.

Despite all of the distortion (and therefore compression) applied to the guitars, Weinstein (1991, p23) states that

> "The heavy metal guitar technique requires great manual dexterity…. The style of play owes much to blues-based guitarists who transformed the urban blues guitar into rock."
> (Weinstein, 1991, P23)

This means that a player requires a sound that is capable of being dynamic as well as powerful and heavily distorted in order to be able to demonstrate their skill as a "Metal God."

## The Alt. Rock Sound

> "Following the blues-rock tradition, heavy metal guitarists were supposed to demonstrate technical proficiency. This emphasis on skill contrasts with the punk [alt. Rock] code; which emphasizes the simplicity of playing, the idea that "hey, anybody can do this, I learned it two weeks ago." Punk stresses a leveling between fans and performers; heavy metal, with its guitar heroes, emphasizes distance."
> (Weinstein, 1991, P24)

For the purposes of this research project, the Alt. Rock sound includes bands such as "The Sex Pistols," and "Nirvana." Through listening to records by these bands it is clear that their guitars are much more dirty that those in the Heavy Metal genre. The guitar arrangements on the records tend to involve simple chords, which are strummed in an almost lazy manner, which often reflects what the songs are about. The lyrics in this genre range from being about depression to anarchism.

This suggests that a player of this genre would not require any dynamics from the distortion. The player would simply want a raw and heavily distorted sound that may even go out of its way to be unmusical to resemble the rebellious nature of the genre.

## The Valve Sound

Michael Leonard, (“Play with your feet”, 2005) stated that,

“Guitarists are prone to drone on about purity. Y’know, how you cant beat the sound of a great guitar going straight into a valve amp.”

Russell O. Hamm (“Tubes vs. Transistors”, 1972, P12) carried out research into why the sound of the valve amplifier is so desirable in all audio applications.

> “A tube amplifier when overloaded generates a whole spectrum of harmonics which give a full bodied, “brassy” quality to the sound. The further any amplifier is driven into saturation, the greater the amplitude of the higher harmonics like the [6$^{th}$, 7$^{th}$ and 8$^{th}$], etc. These add edge to the sound, which the ear translates to loudness information. Overloading an operational amplifier produces such steeply rising edge harmonics that they become objectionable within a 5dB range. Transistors extend this overload range to about 10dB and tubes widen it to 20dB or more.”

Hamm also states that valve amplifiers will exhibit more bass than transistor based equivalents. This is directly related to their strong 1$^{st}$ and 3$^{rd}$ harmonics, which reinforce natural bass with synthetic bass. It is these characteristics that will be sought after in this research project.

## Harmonics

In Hamm's journal "Tubes vs. Transistors" he writes about the "Significance of Musical Harmonics"

> "There is a close parallel…. between electronic distortion and musical tone coloration that is the real key to why tubes and transistors sound different." (Hamm, 1972, P12)

Although the research for this project focuses on the characteristics of different circuits all based around transistors, the same principles of harmonics and tone coloration apply. Hamm goes on to explain exactly how certain harmonics contribute to the overall sound of an instrument.

> "The primary colour characteristic of an instrument is determined by the strength of the first few harmonics. Each of the lower harmonics produces its own characteristic effect when it is dominant or it can modify the effect of another dominant harmonic if it is prominent. In the simplest classification, the lower harmonics are divided into tonal groups. The odd harmonics (third and fifth) produce a "stopped" or "covered" sound. The even harmonics (second fourth and sixth) produce "choral" or "singing" sounds.
> (Hamm, 1972, P11)

Hamm then explains how "the second harmonic is an octave above the fundamental." This added an element of confusion into the research for this project as Hamm ignores the idea of a 1st harmonic, which is generally considered to be an octave above the fundamental. This means that what Hamm describes as even harmonics would be odd harmonics to another person. For the purposes of this project the 1st Harmonic will be deemed as a being an octave above the fundamental.

With this in mind all of the quotes from Hamm's journal that are used in this project will be altered accordingly. The above quote from Hamm's journal should now read like this;

"The [even] harmonics ([second and fourth]) produce a "stopped" or "covered" sound. The [odd] harmonics ([first, third and fifth]) produce "choral" or "singing" sounds."

An experiment will be carried out to prove this effect in more detail in an attempt to discover

1. Which diodes would be more suitable for the recreation of the "valve" sound through the use of a distortion pedal?
2. Which diodes are more suggestible than others for the re-creation of the sounds of the key music genres that have been researched for this project?

The experiment will test 4 different diodes at different gain levels and at different input levels to discover both how dynamic they are and how they react in terms of the creation of harmonic distortion.

# Inside the Distortion Pedal

## Operational Amplifiers

All the pedals studied in this project are based on operational amplifier or transistor based designs so it is important to understand why they are so commonly used. Penfold (1991, P1) wrote that Operational amplifiers "make it very easy to set any desired input impedance and voltage gain figures" This is useful in guitar technology because of the difference in output levels from various guitar pick-ups;

> "The more expensive units have medium output impedances and much higher output levels. In fact some guitar pick-ups apparently have output levels of around 2 volts r.m.s. after the initial peak. This is around one hundred to one thousand times higher than that of the lowest out-put pick-ups."
> (Penfold, 1991, P12)

Transistors and operational amplifiers both allow a varying voltage that is applied to one of its three legs, to control a proportionally larger one between the other two. This is the basic principle behind their amplification capabilities.

In both operational amplifiers and transistors the gain level can be set by adding a resistor into the feedback loop as shown in fig.1.

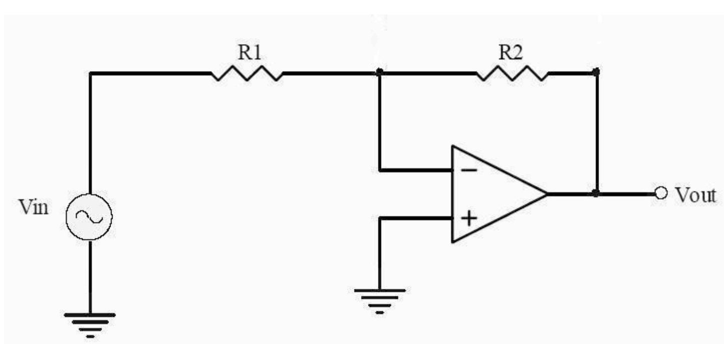


fig.1. Operational amplifier with resistor in feedback loop

Increasing the resistance of R2 will increase the voltage gain of the circuit. Guitarists can use this effect on it's own. It would provide a level boost that when switched into the players signal chain would drive their amplifier further into saturation. Heavy Metal guitarists could use this effect when they play a solo in the middle of a song, as it will give them the extra cut that they need to be heard above the rest of the band.

If back-to-back diodes are placed in parallel with the resistor in the feedback loop (as shown in fig.2) then they will introduce harmonics into the waveform thereby creating distortion. The type of diode used in this feedback loop can greatly affect the distortion produced (discussed below).

## Diodes

Diodes are electric components that resist current in one direction only. All diodes have a forward voltage threshold at which point the diode begins to lose its resistance and will therefore gradually allow a voltage to fluctuate between positive and negative. It is the diodes transition into this resistance drop that determines the type of distortion it produces. As each diode begins to lose its resistance it will introduce harmonics into the signal (which produces distortion).

> "The forward resistance of a germanium diode is quite high at very low, forward voltages, but nothing like as high as the equivalent figure for a silicon diode. Furthermore, the resistance starts to fall at a much lower voltage, and the transition from the "off" state to the "on" state is far more gradual." (Penfold, 1994, P9)

According to Penfold (1994, P3), this means that a germanium diode will have a "full bodied" and more "musical" sound due to the “strong lower harmonics” generated through the process of “soft clipping”. He also claims that the silicon diode will generate “strong high frequency harmonics” (Penfold, 1994, P2) creating a “bright” and more “discordant” sound generated through the process of “hard clipping”.

This immediately suggests that silicon diodes might produce the cutting sound that is desired by Heavy metal players and that germanium diodes would produce the dynamics and valve-like sound desired by blues players.

## Inverting / Non-inverting?

The majority of clipping circuits employed in commercial distortion pedals are based around an inverting operational amplifier with back-to-back diodes in the negative feedback path. This design can be seen in Fig.2 below.

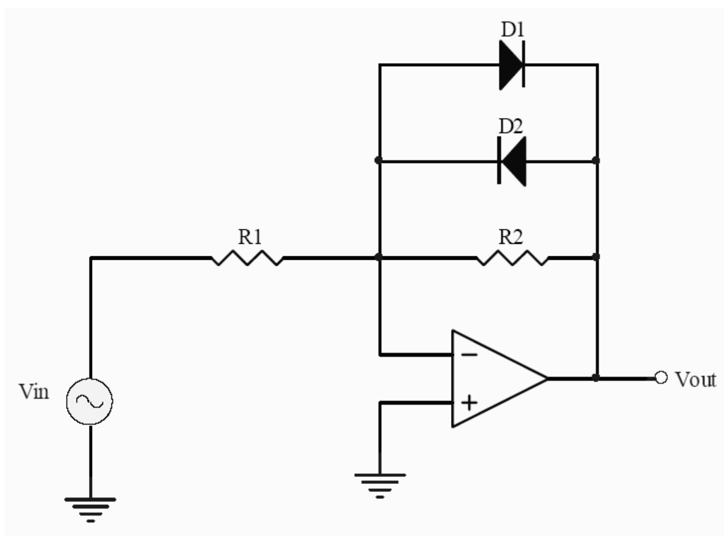


Fig.2. Operational Amplifier based Inverting Clipper (Topaktas, Tube Screamer's Secret, 2005, online)

When the diodes reach their forward voltage threshold they clip the waveform in a hard or soft manner depending on the type of diode employed in the circuit (as described above). This has the effect of rounding off the top of the waveform as shown in Fig.3a.

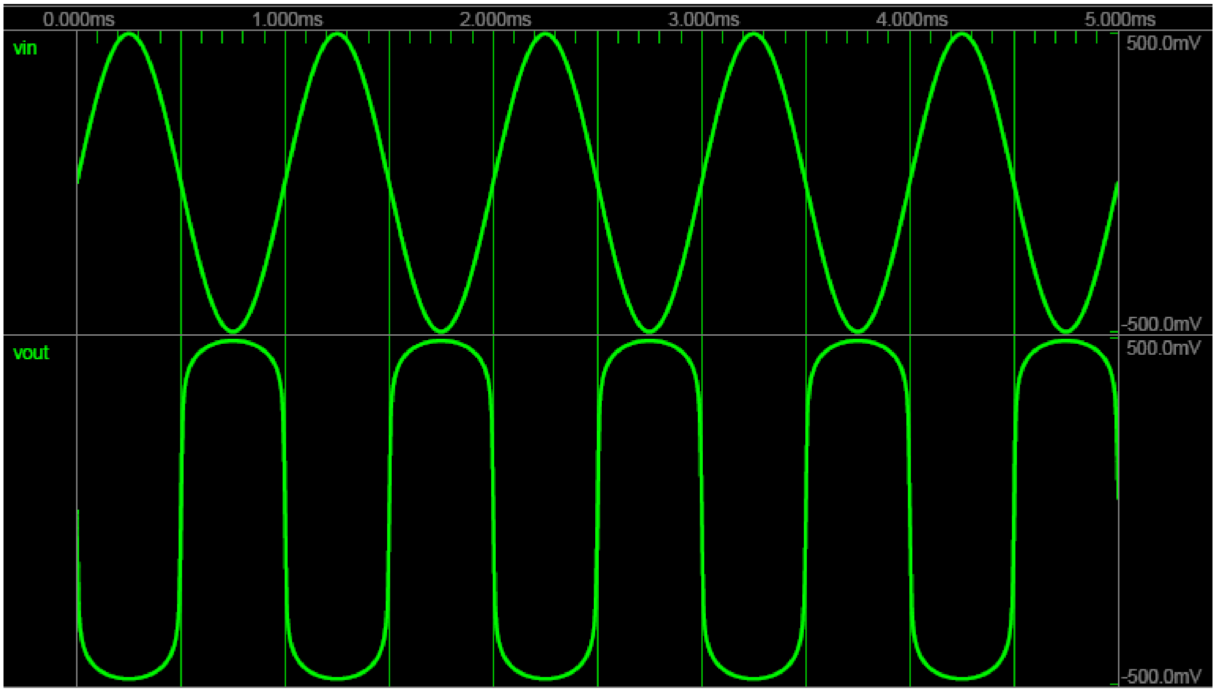


Fig.3a. Input and Output waveforms of the inverting clipper (Topaktas, Tube Screamer's Secret, 2005, online)

According to Topaktas (Tube Screamer's Secret, 2005, online)

> "when the same circuit is modified so that the input voltage is applied to the non-inverting input of the operational amplifier (i.e. the circuit is converted to operational amplifier based non-inverting amplifier)….the output waveform of the non-inverting clipper consists of two components: (1) the amplified and clipped version of the input waveform (2) plus the un-amplified input waveform. That is, the non-inverting clipper adds (or mixes) the original input signal to the amplified and clipped input signal."

The output waveform is now as shown in fig.3b.

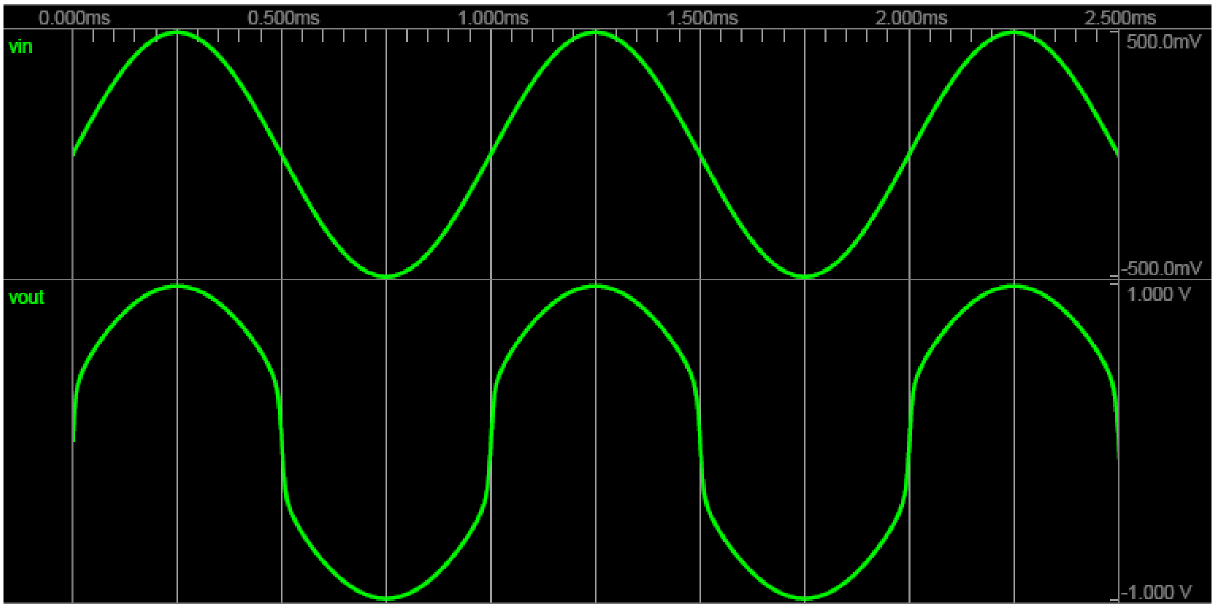


Fig.3b. Input and Output waveforms of the noninverting clipper (Topaktas, Tube Screamer's Secret, 2005, online)

Fig.3b clearly shows that the original input signal can be seen in the clipped output.

> "Mixing the input signal with the output signal of the clipper preserves the original dynamics of the input signal which otherwise would get lost at the threshold of clipping. Preserving original dynamics of the input signal avoids muddiness and vastly improves clarity and responsiveness."
>
> (Topaktas, Tube Screamer's Secret, 2005, online)

The dynamics and natural sound exhibited by this pedal would seem ideal for the blues player. It may also be possible (with a suitable choice of diode) to create the sound required by a Heavy Metal player. If a hard clipping diode was used along with a non-inverting operational amplifier then heavy distortion could be achieved whilst still preserving the subtleties of the playing.

# The Experiment

# Process

A simple distortion pedal was adapted from a schematic from www.smallbearelec.com called "The Tweak-O". The pedal was originally designed to be built on perforated board. For the purposes of the experiment the pedal was adapted to be built on breadboard, which would allow components to be interchanged easily for testing. The schematic is shown in fig.4.

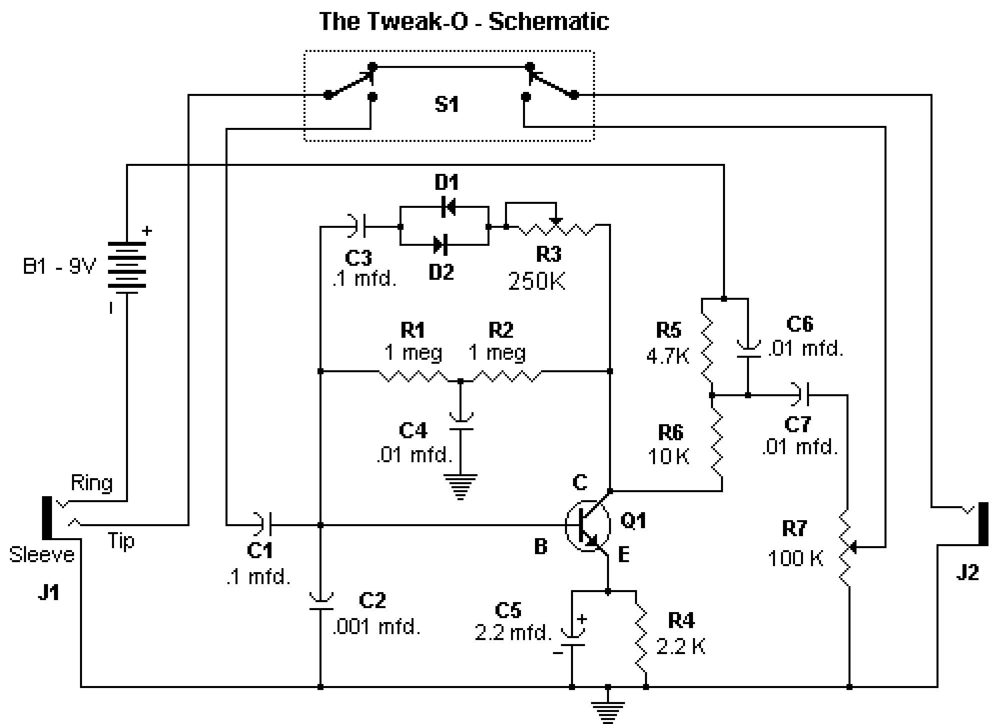


Fig.4. Schematic for the pedal that was built and used for testing (Davison, J, "The Tweak-O", online.)

The original schematic suggested that two silicon diodes were used in the clipping circuit (D1 and D2). In the experiment different diodes were tested in place of these two. The chosen diodes were germanium, silicon, rectifiers and LEDs.

In turn, each of the diode pairs were placed in the circuit in place of the original D1 and D2. A 400Hz sine wave was sent through the pedal at levels varying from 0dB to –54dB at 3dB intervals and the output was recorded into Pro-Tools. On top of this each pair was recorded with R3 (the potentiometer immediately after the diodes that sets the gain level) set at different resistances. The transfer function of the pedal and also the harmonic content of the signal were measured for each sample.

To measure the harmonics, a "Waves PAZ analyzer" was inserted over the output of Pro-Tools. The analyzer was capable of measuring all of the harmonics up to the 10th in most cases. At higher gain settings, harmonics above the 8th began to merge together on the visual display of the Waves Analyzer, making the test less accurate. However, according to Hamm "The primary colour characteristic of an instrument is determined by the strength of the first few harmonics" ("Tubes vs. Transistors" 1972, P11). This means that inaccuracies above the 8th harmonic are not detrimental to the results of the experiment. The readings were taken despite them not being accurate because in some cases, as the input signal approached 0dB, the only changes to the harmonic spectrum were to those upper harmonics which Hamm states are directly related to the "loudness" of a signal.

The transfer function of the pedal was measured in order to see how each diode could affect the dynamics of a guitarists playing. A linear transfer function could prove to be more suitable for those players who use expression in their playing where a non-linear transfer function would apply compression to a signal that may be more suited to players who desire more power from their sound.

It must be noted that the input signal was adjusted in 3 dB intervals starting at 0dB and finishing at –54dB. This means that there are no absolute values recorded in this project. The recorded output signals were actually measured as being lower than the input but this was due to the input gains into Pro-Tools being set too low. This would not affect the outcome of the experiment, as the gain remained the same for all of the tests.

# Experiment Results

**Harmonic analysis results with no resistance from R3**

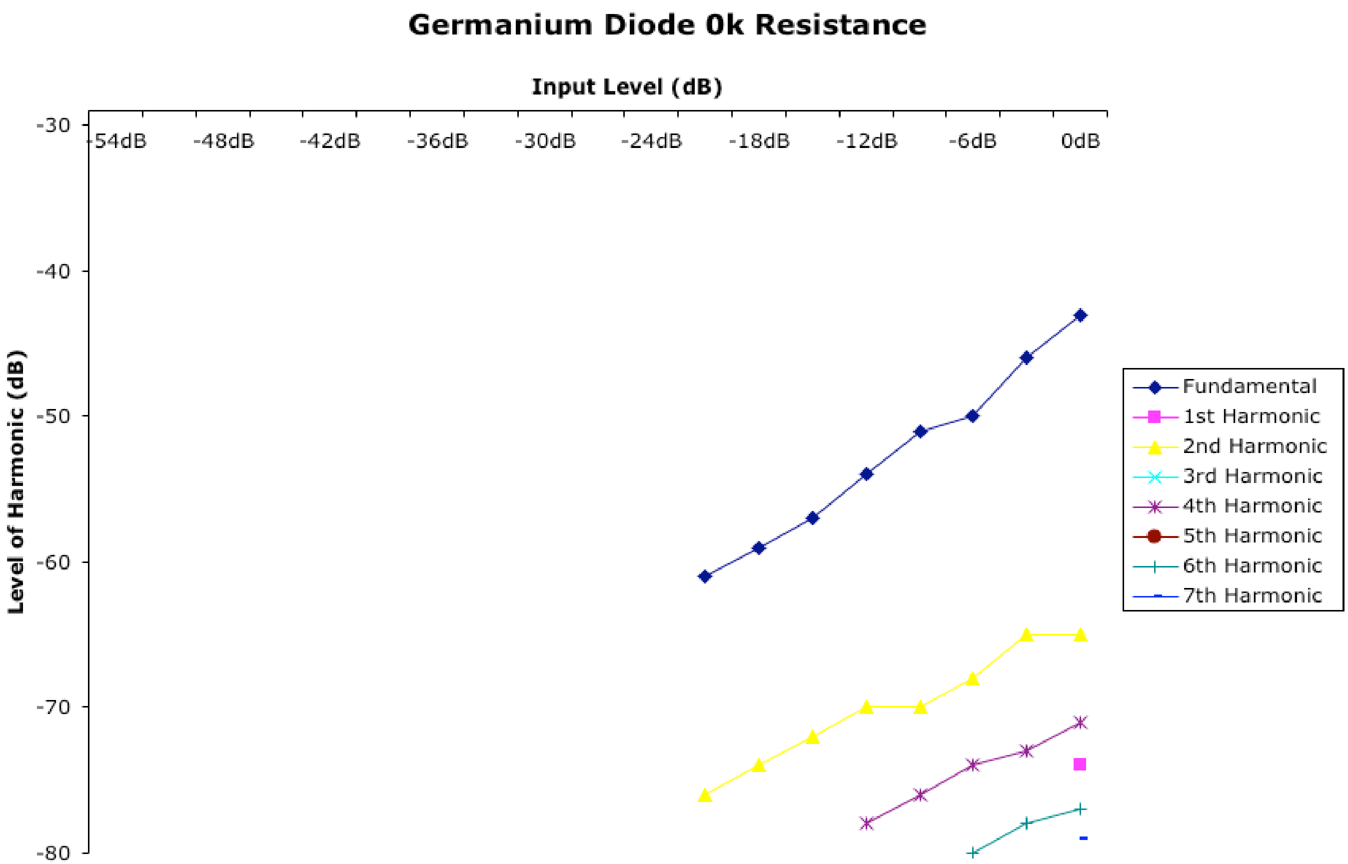


Fig.5. Germanium diodes set with no resistance from R3

Fig.5. shows that pedal produced no output until the input reached –21dB. The second harmonic was dominant as soon as a signal began to pass through the pedal (along with the fundamental). The 4th harmonic began to rise 9dB later followed by the third harmonic after a further 6dB. The harmonics' levels increased linearly when they were introduced right up until the input reached 0dB. The 3rd harmonic was introduced at –6dB and rose in parallel with the even harmonics. At 0dB the 1st and 7th harmonic appeared, the 1st at a level of –54 dB (just below the fourth. The 7th appeared at a level of –79dB.

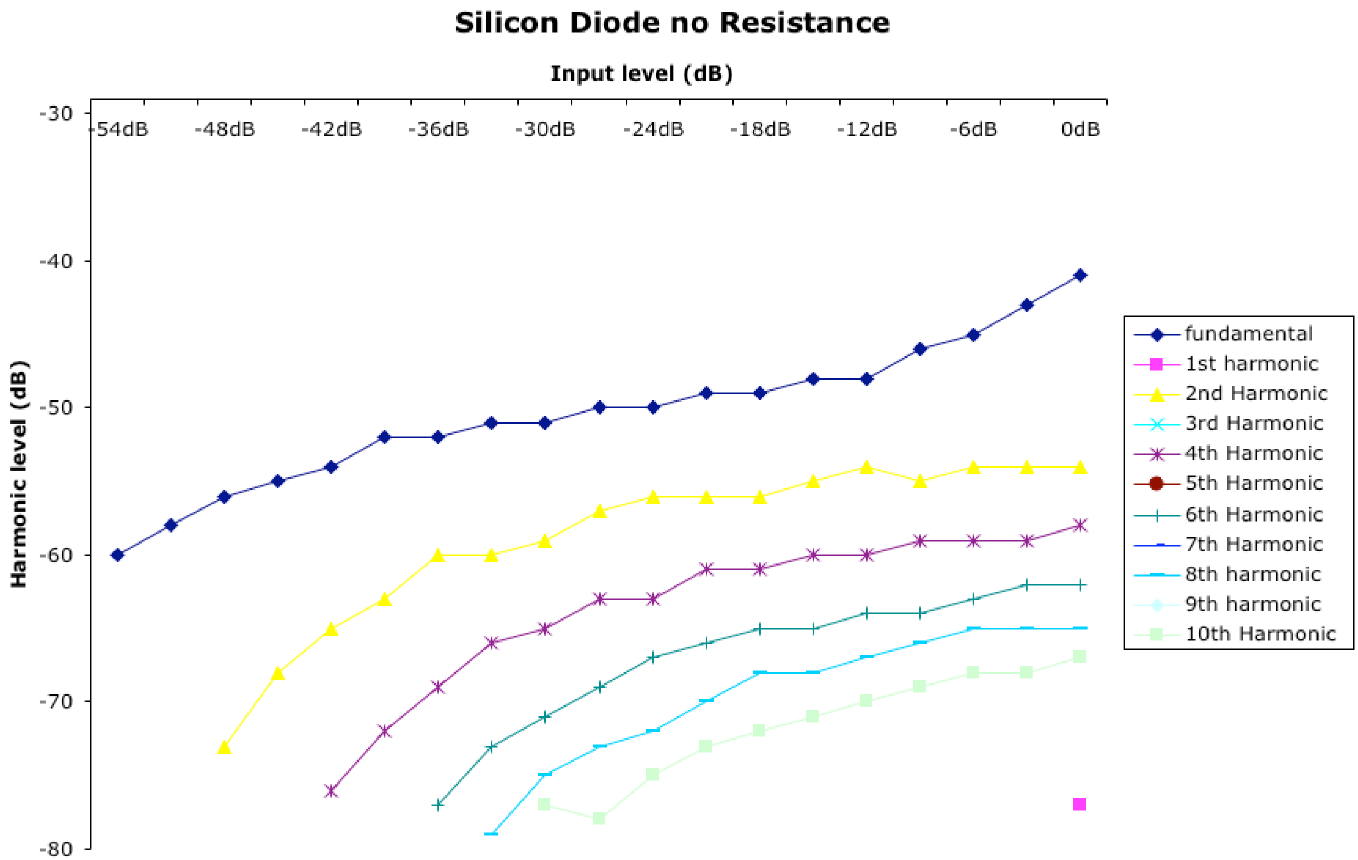


Fig.6. silicon diodes set with no resistance from R3

Fig. 6 shows that the pedal produced a clean output from an input of –54dB through to –48dB with no harmonics present. This set of results saw the 8th and 10th harmonics introduced, which were not present in the results for the germanium pair. The harmonic levels also rose in a more non-linear fashion and in parallel with each other. The 1st harmonic was not introduced until 0dB and it was 12dB lower in level than any of the other harmonics. Interestingly, the 1st was the only odd harmonic in this set of results.

The 2nd harmonic was dominant and rose 6dB after the fundamental was introduced. This was followed by the 4th 6dB later, the 6th after a further 8dB and the 8th after a further 3dB (all at progressively lower levels).

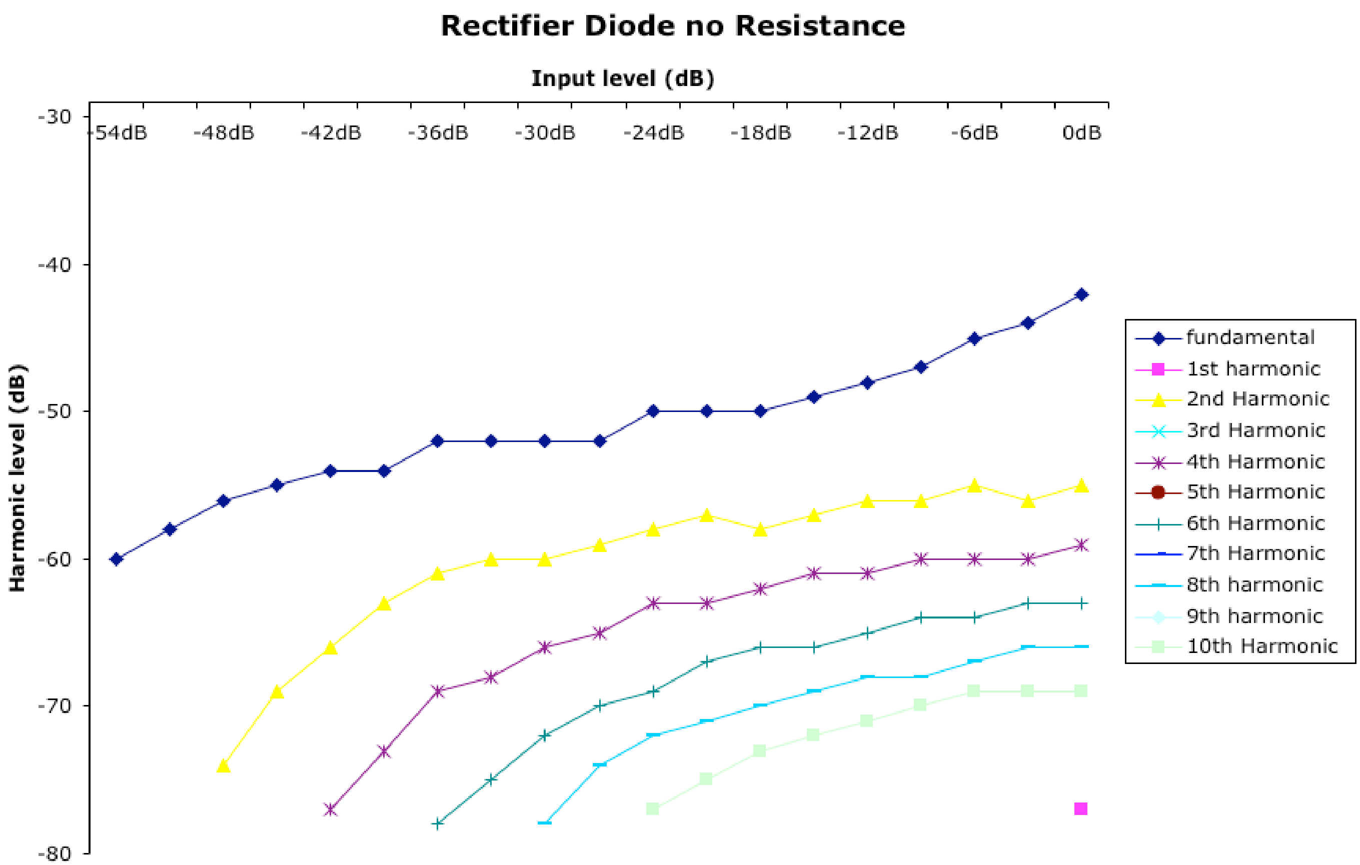


Fig.7. rectifier diodes set with no resistance from R3

Fig.7. shows that the rectifier diodes produced exactly the same results as the silicon pair. The harmonics were on average 1dB lower in level than in the silicon test but this could be put down to experimental error.

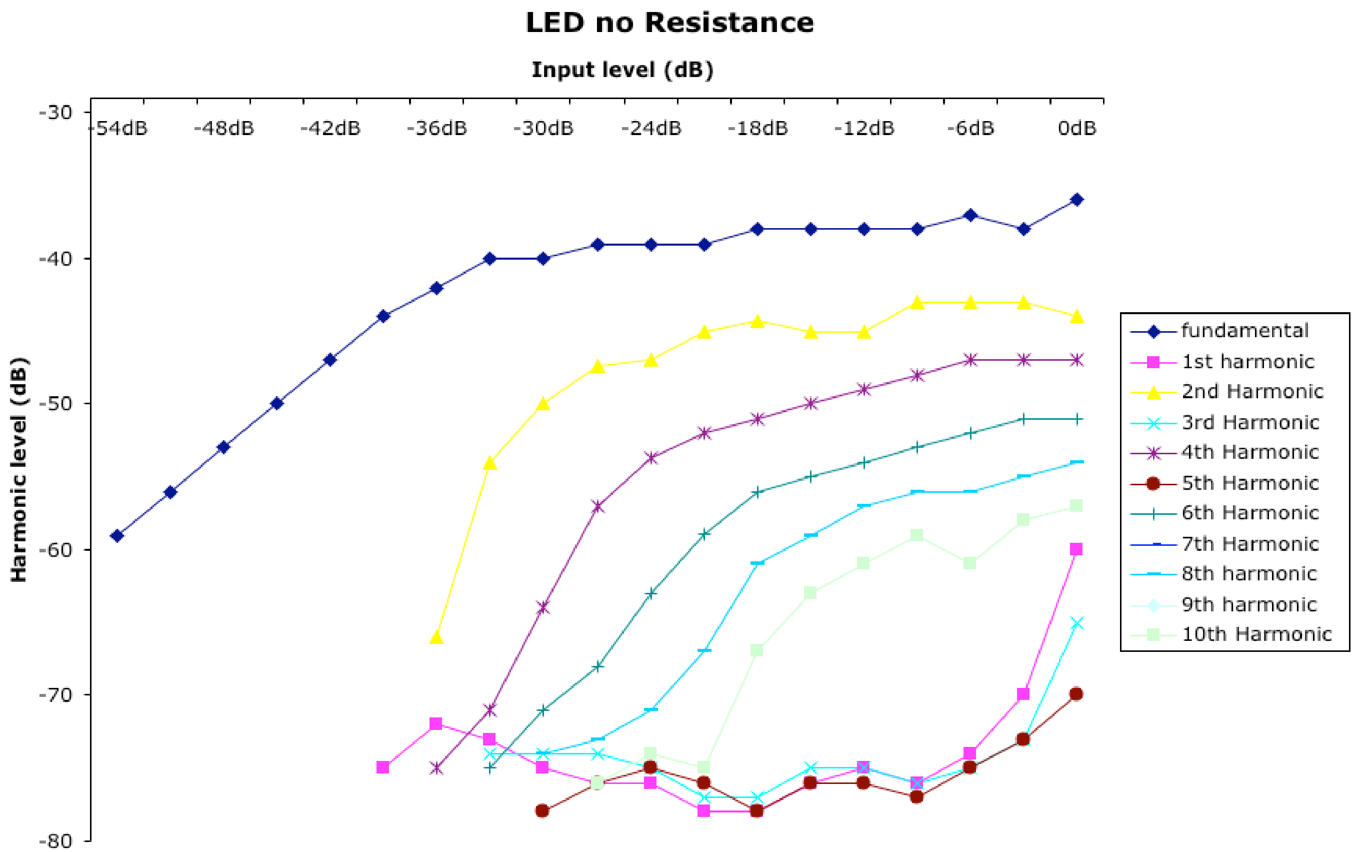


Fig.8. LEDs set with no resistance from R3

Fig.8 shows that the pedal produced a clean output from –54dB through to –39dB. An interesting feature of this set of results is the early presence of three odd harmonics, the 1st, 3rd and 5th. Although these harmonics remained below –72dB until the –3dB input level was reached it was surprising that the 1st harmonic was introduced before any of the even harmonics.

The even harmonics were all introduced within 6dB of each other and rose in parallel together in a non-linear fashion. They began to rise very sharply then quickly slowed down and increased gradually until 0dB was reached. At –9dB the odd harmonics rose sharply in level and carried on doing so until 0dB was reached.

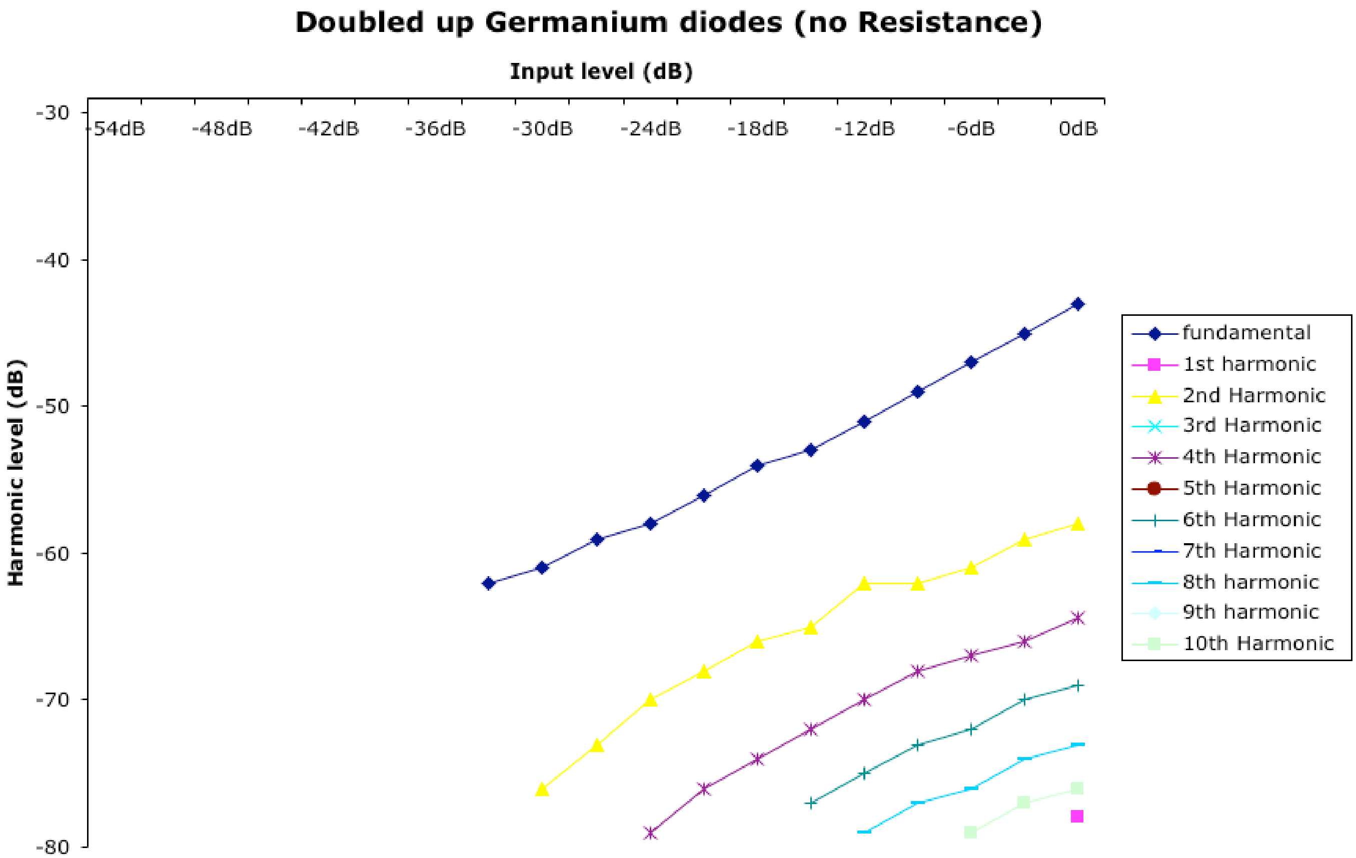


Fig.9. 2 pairs of germanium diodes in series set with no resistance from R3

Fig.9 shows that the pedal produced no output until the input level reached –33dB. There were no odd harmonics present until the input reached 0dB when the 1st harmonic was introduced at a level of –78dB. The 2nd harmonic was introduced only 3dB after the fundamental. The results now began to show the non-linearity exhibited by the other diode types. All of the harmonics up to the 10th were present and rose in parallel with each other. The 4th was introduced 6dB after the 2nd, the 6th was introduced after a further 9dB, the 8th after a further 3dB and the 10th after a further 6dB.

**Analysis of the results of harmonic tests with 0Ω resistance from R3**

The silicon and rectifier diodes behaved identically in the harmonics tests at this stage. The germanium diode has a lower forward voltage threshold than the silicon, rectifier and LED. This explains the much lower output level that they exhibited. Although the test with only one pair of germanium diodes appeared to show a limited but linear response, it became clear that the results were only showing part of their response when the second test was carried out using two pairs instead of one. This would have the effect of raising the forward voltage threshold to something closer to that of silicon and rectifier diodes. With this set-up a larger voltage can be passed through them before they will begin to lose their resistance and clip the signal. Their response was still very linear but it exhibited a very similar harmonic pattern to the silicon and rectifier diodes.

As the maximum input level was approached the harmonics produced by the germanium diodes were still rising very linearly. All of the other diodes had shown signs of non-linearity before the input had reached –24dB which shows that the signals were being compressed. The addition on the 2$^{nd}$ pair of diodes had without doubt extended their range. The addition of a 3$^{rd}$ pair would most likely increase this further making them the ideal choice for any player wishing to use dynamics in their playing.

The LEDs were the only diodes that produced an output that was significantly different harmonically to the rest of the diodes tested at this resistance. It could be concluded that the LEDs were the least dynamic at this resistance because all of the even (and most dominant in this case) harmonics were introduced within 6dB of each other. It could also be concluded that the LEDs were the 2$^{nd}$ most dynamic diodes (behind the germanium pairs) because despite the fact that all of the even harmonics were introduced within 6dB, they rose significantly more than any of the other diodes in the given range and were still rising when 0dB was reached.

The LED was however, the only diode that produced a 1st harmonic from the beginning of its clipping point. “Musically the [1st] is an octave above the fundamental and is almost inaudible; yet it adds body to the sound, making it fuller.” According to Hamm’s research valve amplifiers exhibit a strong 1st, 2nd 3rd and 4th harmonic. Where all the diodes in this test exhibited strong 2nd and 4th harmonics, the LEDs were the only diodes to produce the 1st and 3rd harmonics for an extended period of time. In this way LEDs behave more like valves than any of the other diodes tested at this stage.

The silicon and rectifier diodes would make it very difficult to add expression into playing as they began to clip at very low input levels and reached their maximum clipping point very quickly. They also produced strong 2nd 4th and 6th harmonics throughout their clipping range (more so than any of the other diodes). According to Hamm this sound would be “metallic with a very harsh edge that the ear hears as strong distortion.”

**Harmonic analysis results with 100kΩ resistance from R3**

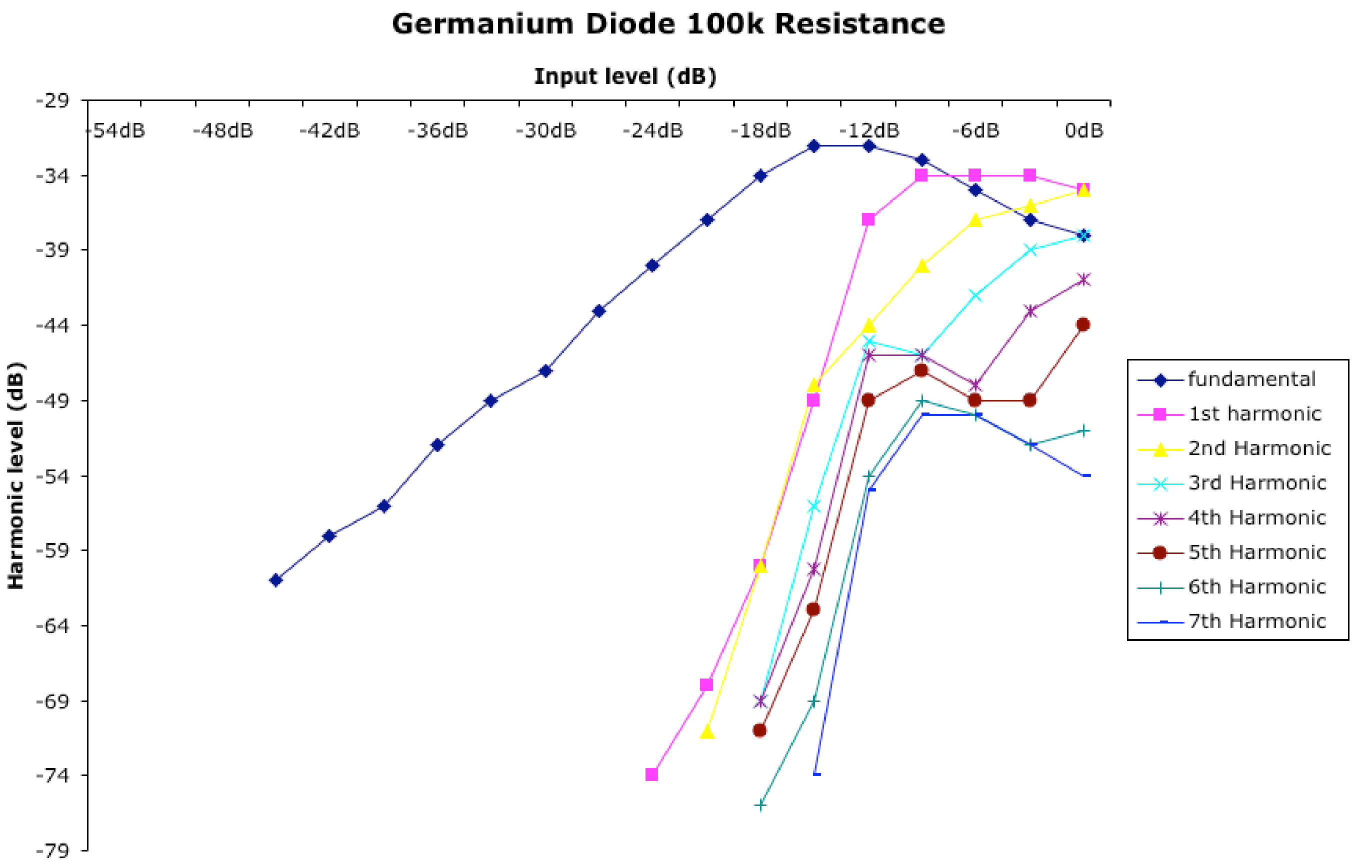


Fig.10. Germanium diodes set with a resistance of 100kΩ from R3

Fig.10 shows that the pedal produced no output until the signal reached –45dB but it then remained clean (no harmonics) for 21dB. Interestingly, the 1st harmonic was the first to be excited and it remained dominant for the remainder of the test. The 2nd harmonic appeared after a further 3dB and remained at a similar level to the 1st harmonic until the input reached –15dB where it began to level out and allow the 1st to become dominant. The next most dominant harmonic was the 3rd, which followed a path in close parallel to that of the 2nd. The remainder of the harmonics rose in close parallel with the 2nd and third in progressively lower levels but all within 6dB (output level).

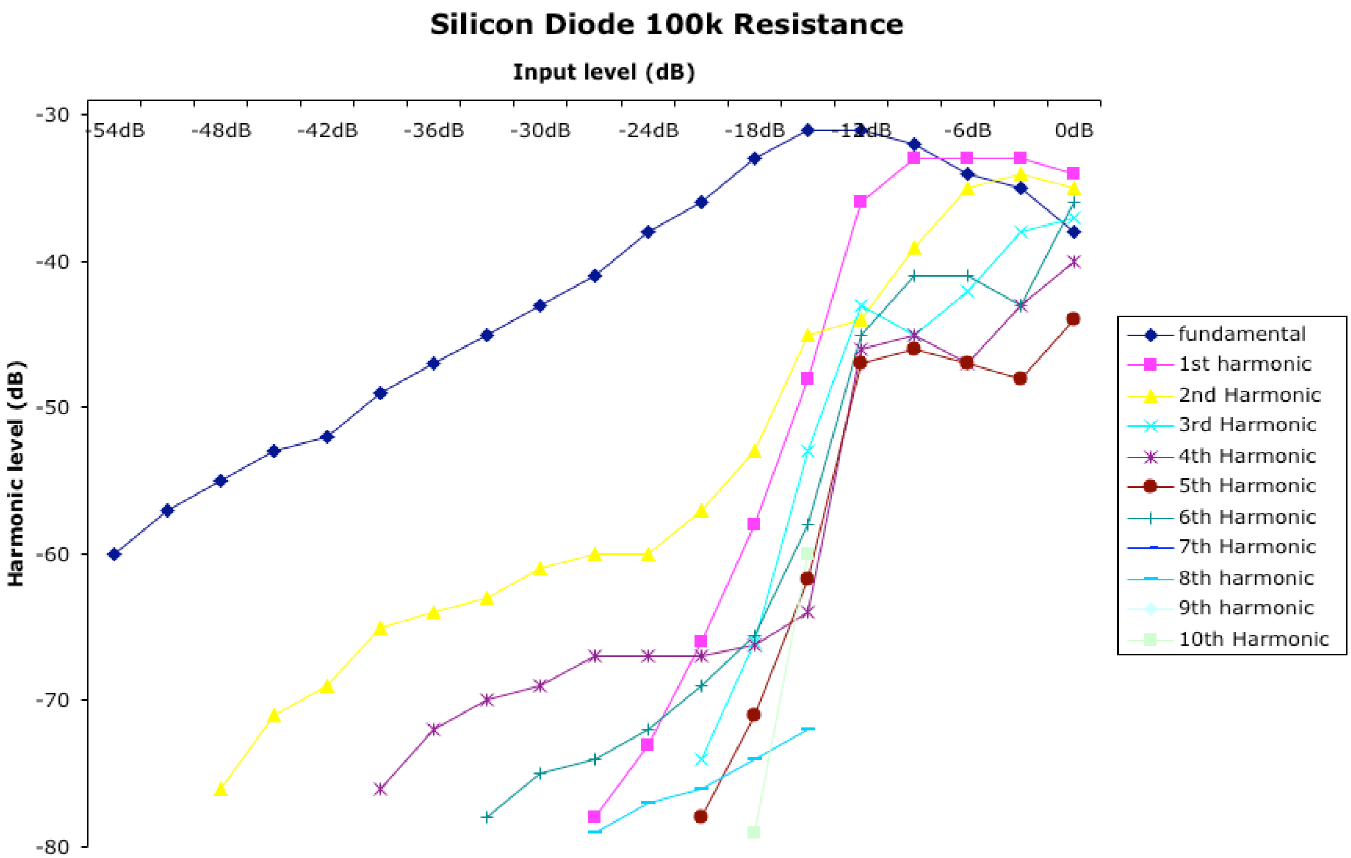


Fig.11. silicon diodes set with a resistance of 100kΩ from R3

Fig.11 shows that the pedal produced an output at –54dB and it remained clean for 6dB when the 2nd harmonic rose in similar fashion to the way it had done with 0Ω resistance. The response of the 2nd, 4th, 6th and 8th harmonic followed the same curves as they had done in the 0Ω test until –24dB when the 2nd began to rise more sharply, closely followed by the 4th and 6th. At the same time in which the 2nd began its sharp increase in level, the 1st harmonic also rose sharply and within 15dB had become the dominant harmonic in the signal. The 1st harmonic was closely followed by the 3rd and 5th, although they levelled out following a similar curve to the even harmonics.

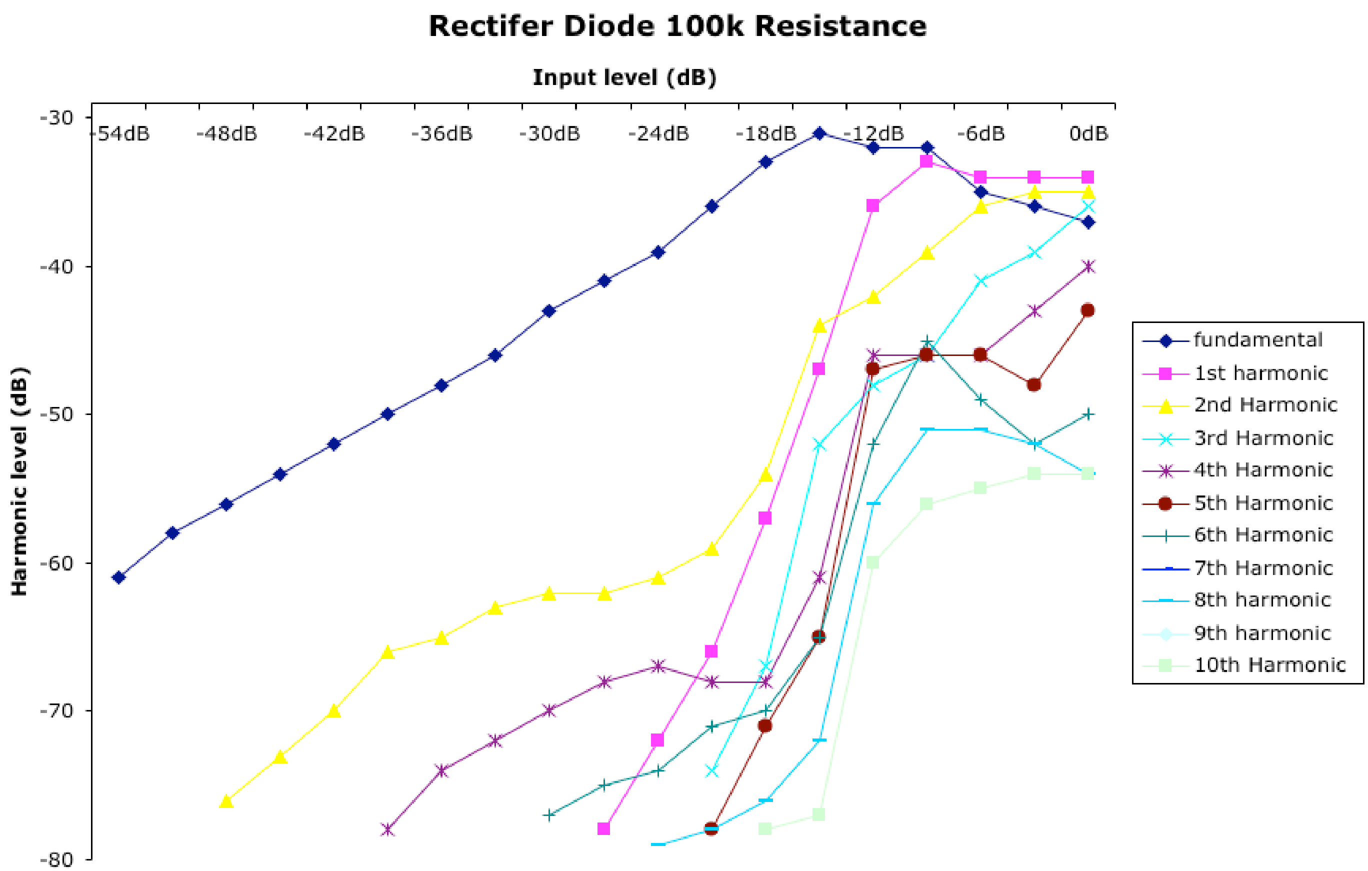


Fig.12. rectifier diodes set with a resistance of 100kΩ from R3

Fig.12 proves once again that rectifier diodes behave in exactly the same way as silicon diodes.

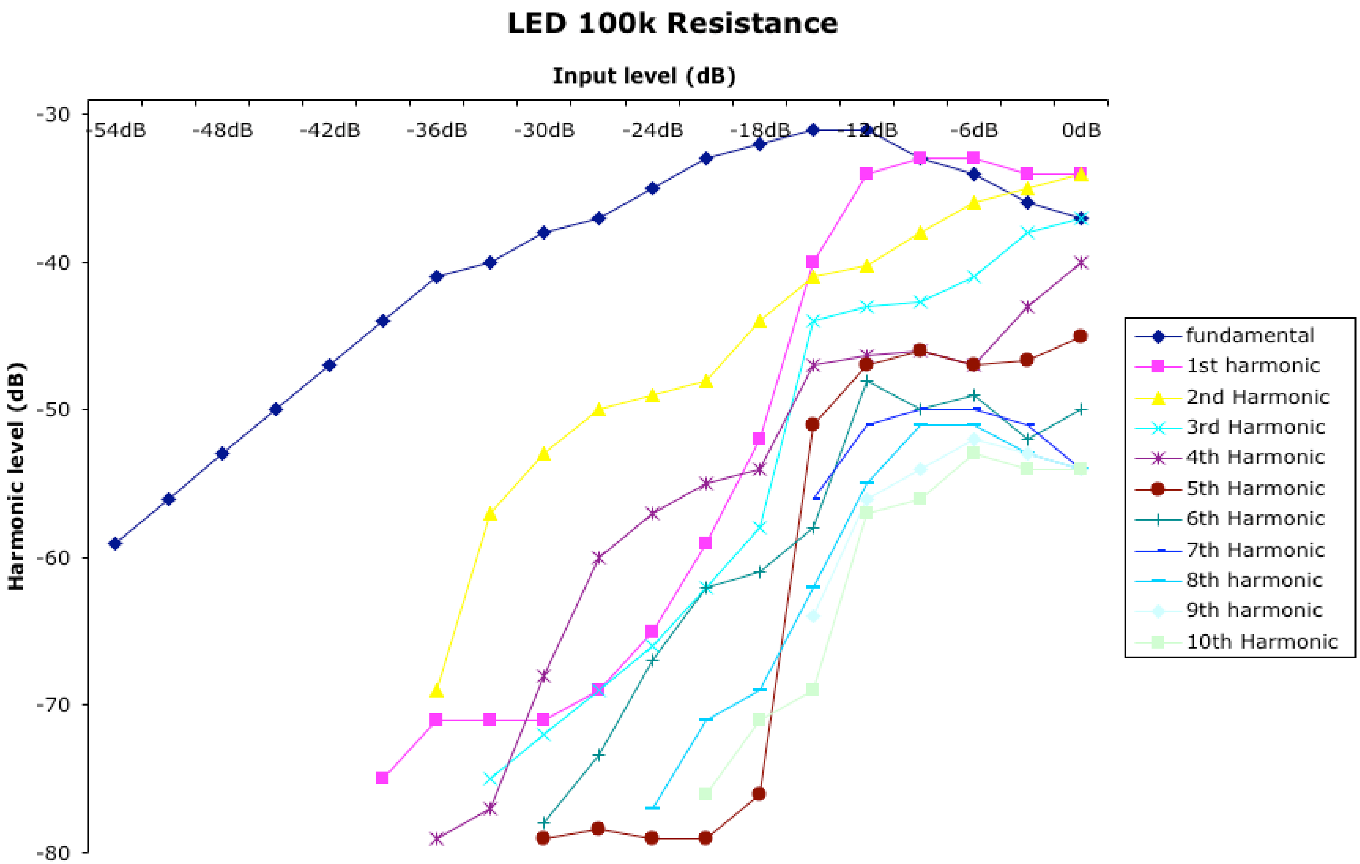


Fig.13. LEDs set with a resistance of 100kΩ from R3

Fig.13 shows that the curves exhibited by the even harmonics closely resembled those produced by the even harmonics in the test at 0Ω resistance. The main difference was that the curves did not level off to such an extent in the test at 100kΩ. The harmonics carried on rising up until the input reached 0dB with only a slight softening in the response. The odd harmonics were much more dominant at this resistance, the 1st harmonic became dominant at an input of -15dB. It remained under –71dB until the input reached –27dB then it began to rise sharply until it levelled off at –34dB (output). This was closely followed by the 3rd and the 5th, which followed a similar pattern but began to level off at –44dB and –51dB respectively.

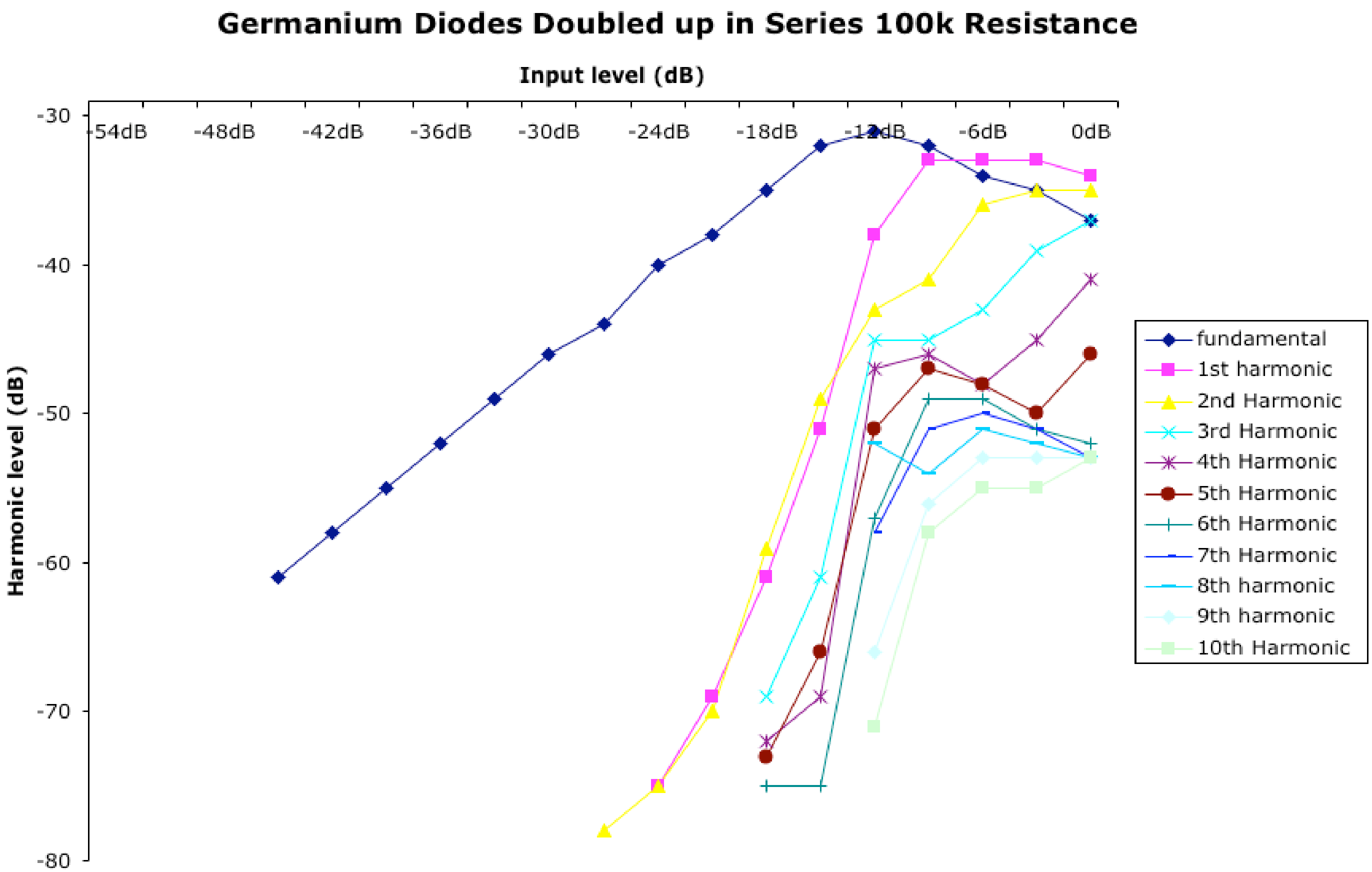


Fig.14. 2 pairs of germanium diodes set with a resistance of 100kΩ from R3

Fig.14 shows that the pedal produced no output until the input reached –45dB and remained clean for 18dB when the 2nd harmonic rose followed by the 1st harmonic 3dB later. The pedal behaved in an almost identical manner to the same setup but with only one pair of diodes. The main difference was the introduction of the 9th and 10th harmonics, which rose as the input approached 0dB.

## Analysis of the results of harmonic tests with 100kΩ resistance from R3

The key characteristic of this set of results is the sudden surge in harmonics that rose between –21dB and –12dB. All of the diodes appeared to show similar characteristics to those they had shown in the test with no resistance from R3 up until this point. Due to the fact that it happened to all of the diodes at approximately the same input level it is possible that this is the point at which the transistor began to overload (making the test results from this point onwards inaccurate). In order to test this theory and to produce some subjective test results, a test was set up whereby 3 guitarists were asked to play their guitars through the pedal and describe what they heard.

## Subjective Listening Test

The following table shows some of the comments that were made by the guitarists when playing through the different diodes, both at no resistance and 100kΩ resistance from R3.

| Diode Type | No resistance | 100KΩ resistance |
|---|---|---|
| **1 Germanium pair** | Too low an output to be a useable effect | When strummed hard it crackles.<br>Quite a lot of bass,<br>Sounds like two guitars, one clean and one distorted |
| **Silicon** | Loads of distortion,<br>Not much bass,<br>Lots of bite,<br>Little or no dynamics.<br>Lots of sustain,<br>All distortion, no chord comes through,<br>Quite sinister,<br>Gets thicker as you play louder | More bass than with low resistance,<br>No dynamics,<br>Sounds clean but with distortion over the top.<br>More attack |
| **Rectifier** | Lots of Sustain<br>Lots of top end<br>Not very bassy<br>Metallic sounding<br>Very grunge sounding.<br>Sounds warm and uncompressed, very raw. | Loads more bass<br>Still lots of sustain but not as distorted.<br>Not dynamic,<br>Sounds like a guitar with just a buzz in the background,<br>Not very tuneful. |
| **LED** | Capable of being played clean as well as distorted.<br>Loads of sustain,<br>Lots of body | Sounds less distorted but crackles when played harder, it sounds sharper.<br>More bass,<br>Can hear the original clean guitar sound making chords clearer. |
| **2 Germanium Pairs** | Lots of Bass,<br>Low distortion,<br>Dynamic,<br>Played quiet there's no distortion at all.<br>More distorted when playing chords.<br>Sounds warm. | Less distorted,<br>Crackles when played loudly.<br>Classic blues sound,<br>Distorts quite suddenly when playing louder. |

All of the guitarists agreed that increasing the resistance of R3 caused a reduction in the level of distortion produced. They also agreed that when playing aggressively at 100kΩ of resistance, they heard a crackling sound that was not pleasing.

The reason for this could be down to one major floor in the initial experiment. Although it can be said that the full range of the pedal's distortion characteristics were covered by the 54dB range of input levels (because the output signal began clean and ended with all the harmonics levelling off at their peaks), the range of a real guitar signal is uncertain. Given that the guitarists on the listening test heard less distortion with the resistance turned up it is fair to assume that the guitars output level would operate normally somewhere just before the point where there was a surge in harmonics. This would also explain the "crackling" sound that some players heard when they played very aggressively. It is therefore entirely possible that the crackling sound was no longer that of the diodes clipping but was actually the point where the transistor began to overload.

The increase in resistance also produced a significant increase in volume, which is shown in fig.15 and fig.16. Fig.15 shows the test results for the transfer functions of all diodes with no resistance from R3 and fig.16 shows the results with 100kΩ resistance from R3.

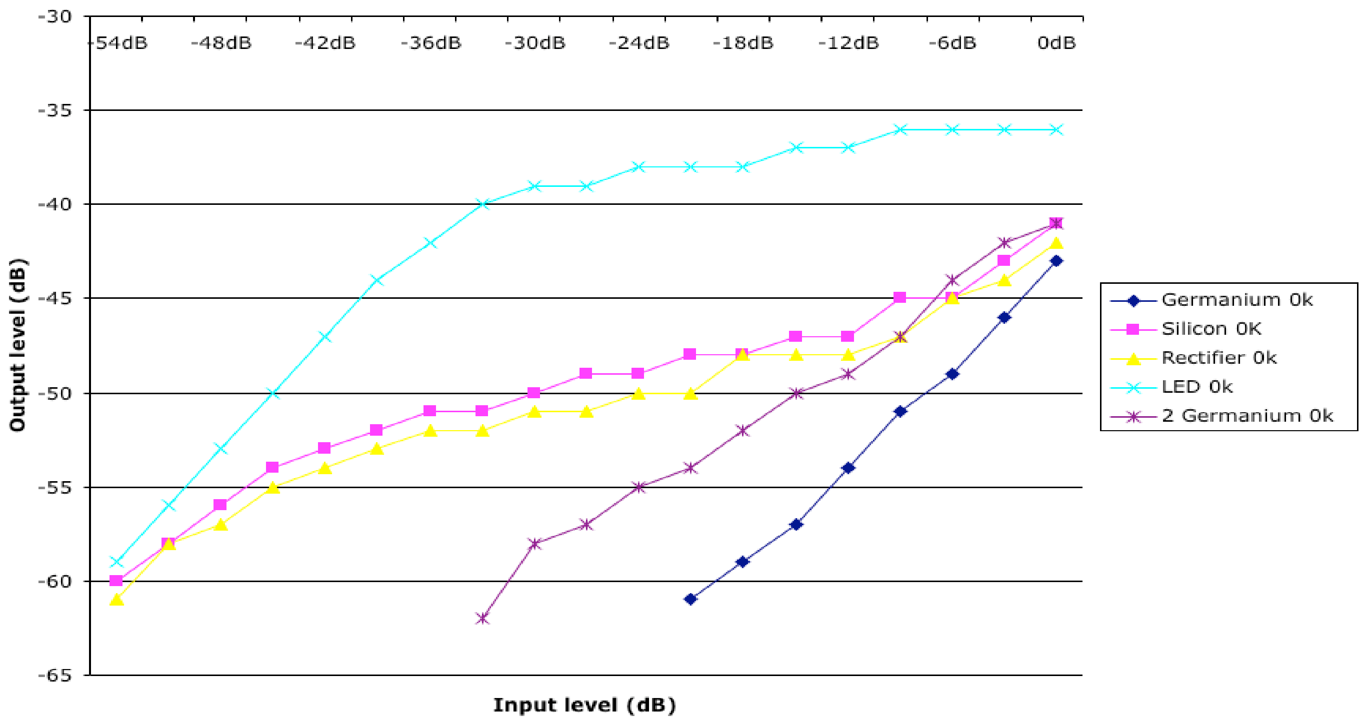


Fig 15. Transfer functions of different diodes with 0Ω resistance from R3

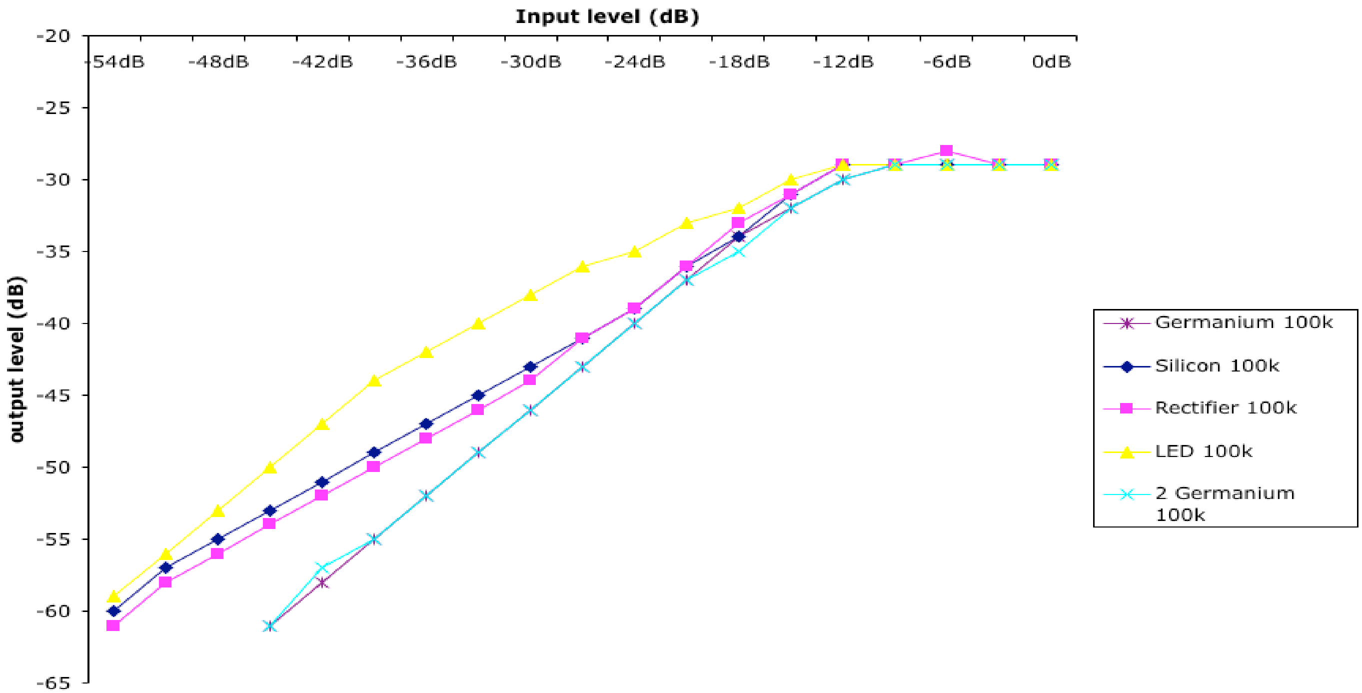


Fig 16. Transfer functions of different diodes with 100kΩ resistance from R3

Fig.15 clearly shows that the diodes were compressing the signal in their own characteristic ways when there was no resistance from R3. Fig.16 shows that the diodes were barely compressing the signal at all until the –21dB input level was reached. At this point the signals began to exhibit signs of compression as the transistor approached its overload point. This means that the resistance of R3 limited the effect that the diodes had on the circuit and as a result, the distortion produced by the overloading of the transistor far outweighed the distortion produced by the diodes.

The limiting effect of R3 on the diodes distortion producing capabilities explains why the guitarists described hearing two sounds (one clean and one distorted). When the resistance of R3 was increased it allowed more of the original clean signal to reach the output. This is a similar effect to that of the non-inverting operational amplifier design. Further tests showed that decreasing the amount of resistance from R3 raised the point at which the transistor overloaded. Fig.17, fig.18 and fig.19 show this effect.

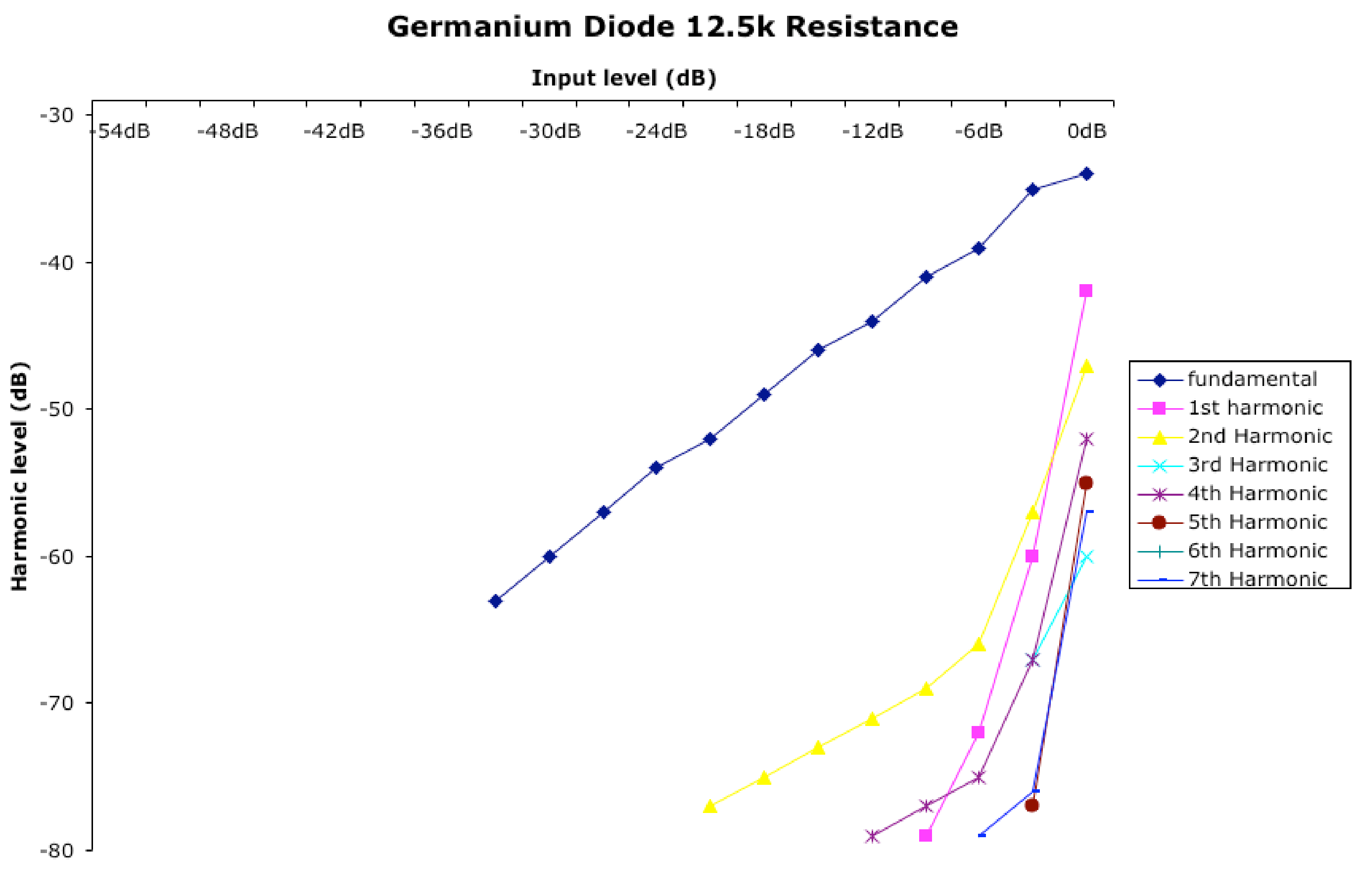


Fig 17. Germanium diode with 12.5kΩ resistance from R3

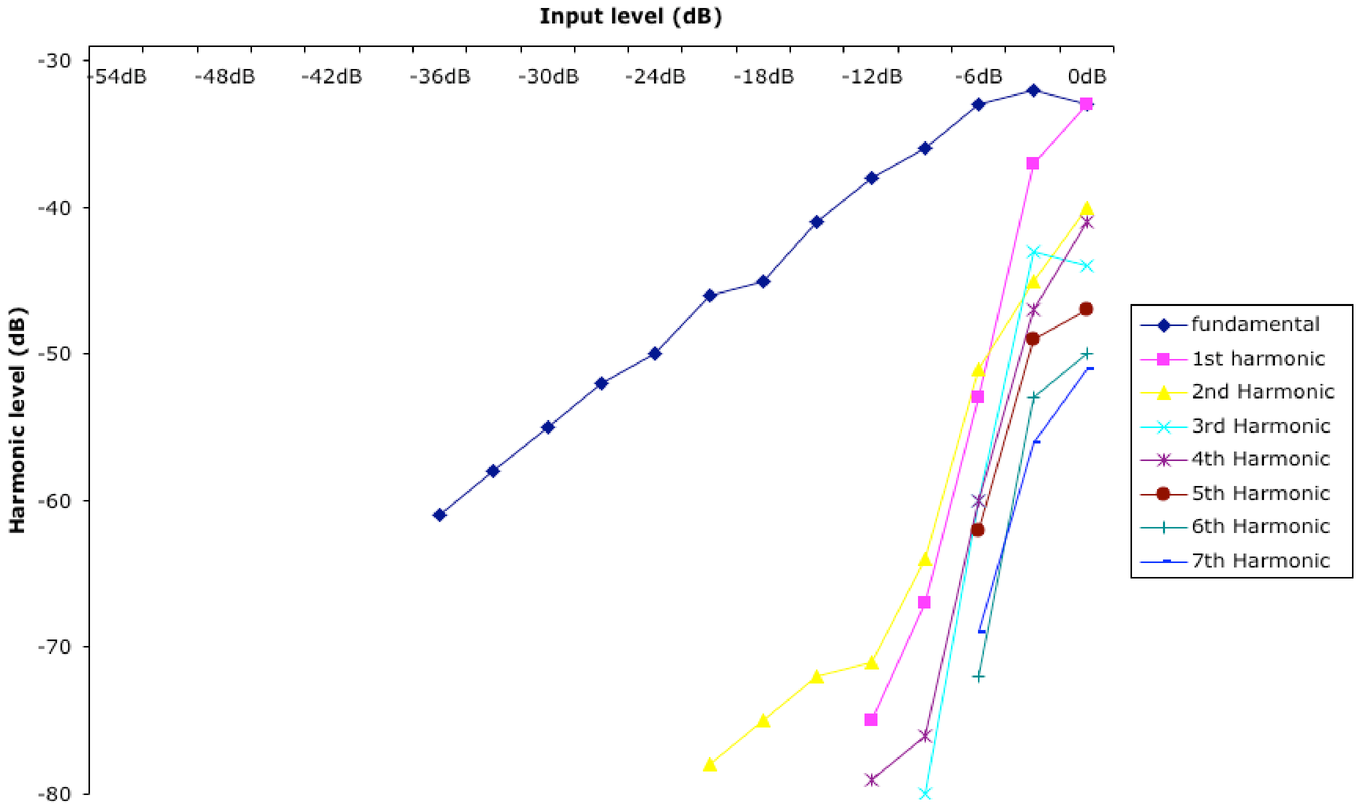


Fig 18. Germanium diode with 25kΩ resistance from R3

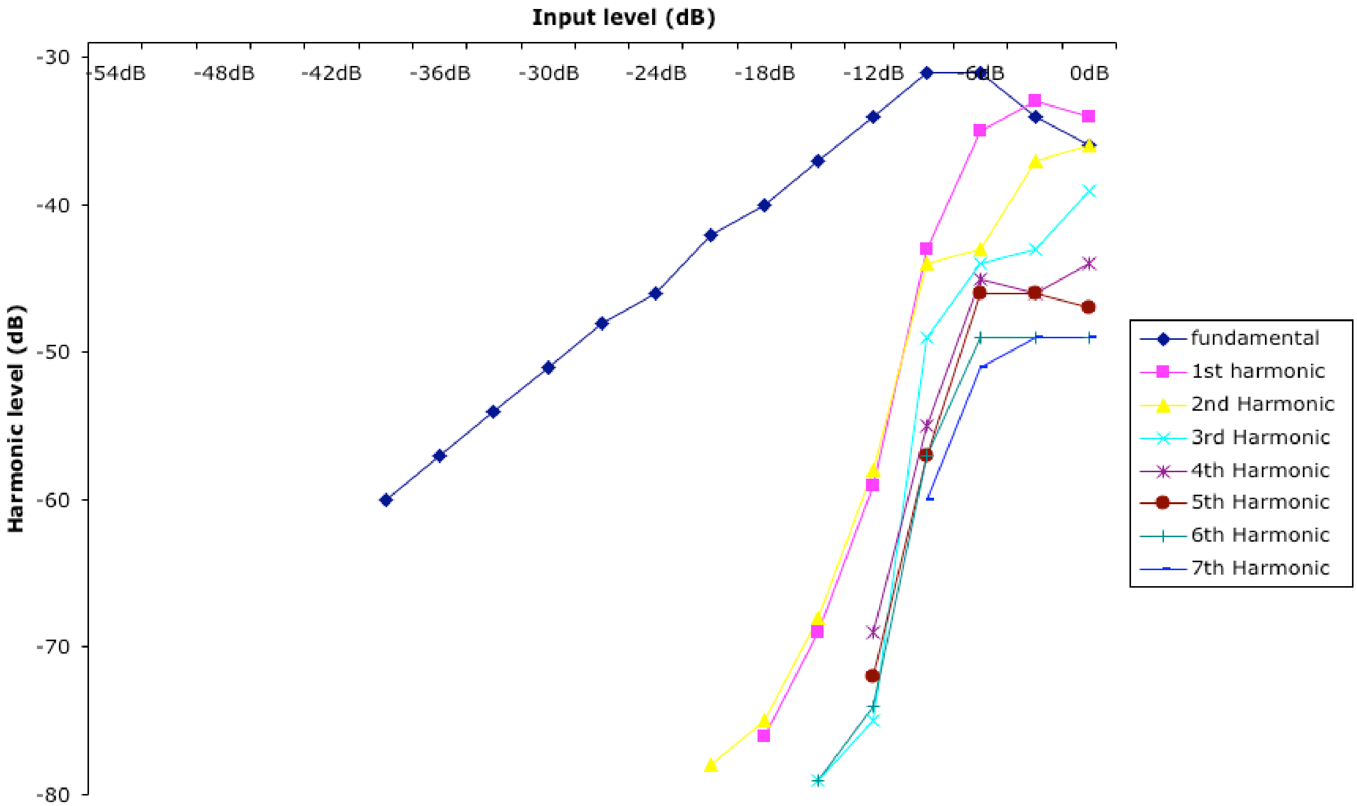


Fig 19. Germanium diode set with 50kΩ resistance from R3

If it was discovered exactly how the range of the guitar signal compared with the range of the sine waves used as the inputs to this experiment then a suitable resistance could be set for the pedal that would make it behave similarly to a non-inverting operational amplifier.

# Conclusions

## Heavy metal

The diode that performed most closely to the requirements of heavy metal genre was the LED. The LED produced the hottest output out of all of the diodes and also included some of the harmonic qualities that give valves their punch. If combined with either a non-inverting operational amplifier based circuit (or a simple transistor based circuit with the correct amount of resistance from the resistor immediately following the clipping diodes), the LED could produce both power and dynamics with high levels of distortion. A booster pedal may also be considered which could be added into the signal chain as well as the distortion pedal. This could drive the player's amplifier further into saturation to produce the upper harmonics that add the bite necessary to cut through the rest of the band for solos.

## Blues

Although the germanium diodes in the experiments carried out in this project lacked dynamic range, adding 3 or even 4 pairs in series could remedy this. The guitarists who tested the pedal all stated that they felt the germanium diode most sounded like a blues pedal even though it was limiting in terms of dynamic range due to the harsh clipping point (which turned out to be the transistor not the diodes). The limited range that 2 pairs of germanium diodes in series produced was very linear, more so than the equivalent results for any of the other diodes tested in the experiment. They remained linear at almost all input levels during test when no resistance was applied from R3. In conjunction with a non-inverting operational amplifier based circuit, the germanium diodes would prove to be extremely dynamic and therefore very suitable for Blues. The test results also showed that with two germanium diodes in series, the 3rd harmonic did not rise until the input level reached –15 dB. This could explain the "warm" and bass heavy sound that was heard by the guitarists who tested the pedal.

## Alt. Rock

Research showed that Alt rock is typically very aggressive sounding. It was decided that the distortion should reflect the genre's anarchistic nature. The silicon diodes produced some very harsh sounding harmonics, which the ear hears as strong distortion, which would therefore be suitable. An inverting operational amplifier would also be more suited to the genre than an inverting one as it would provide a more distorted signal that would sound more aggressive.

The resistor immediately after the diodes should provide only a very small resistance. If a potentiometer was used then it should not have a resistance of more than 25KΩ or too much of the clean signal will be passed through to the output. This value will vary slightly from circuit to circuit.

## The Valve Sound

None of the diodes exhibited all of the characteristics of a valve amplifier. The LED produced harmonic distortion that most closely resembled that of a valve's. It did not however exhibit a strong enough 1st or 3rd harmonic, which give valves their full, brassy quality.

The germanium diodes most closely matched the valve's dynamic range because of their gradual transition into overload. It would be necessary to use three or more pairs of diodes in order to achieve the desired range. With more experimentation it might be possible to produce a pedal that contained two separate clipping circuits. One circuit would contain germanium diodes and the other would contain LEDs. A mix control could be added to control the level of each clipping circuit in the output.

## Evaluation

In order to hone these sounds further, more research should be carried out into other parts of the circuitry such as the equalisation and biasing stages. There are also many different types of transistors that have different characteristics to the transistor tested in this project, whose sounds should be analyzed.

The sound of the valve amplifier has proven very difficult to emulate. One company that specialises in guitar pedals has actually started building distortion pedals with valves built into them instead of diodes. This shows that valves characteristics are very unique. Perhaps guitarists are right when they say, “you can’t beat the sound of a great guitar going straight into a valve amp.” (Leonard, “Play with your feet”, 2005)

It should finally be noted that the above recommendations are not definitive setups for these genres. They are just suggestions that could point a guitarist in the right direction if he was looking for a certain sound.

# Bibliography

Bartlett, Benji, (2005), “Perfect FX set-ups”, Guitarist, Issue 267, August 2005, P72

Bolton, W, (1994), “Principles of Electricity”, Essex, Pearson Education Limited

Cross, Dan, (n.d.), Learn To Play Like B.B. King, online, Available, http://guitar.about. com, (9th December 2005)

Hamm, Russell O, (1972), “Tubes Vs. Transistors (Is There An Audible Difference?)”, Journal of the Audio Engineering Society,

Hunter, Dave, (2005), “The FX Evolution”, Guitarist, Issue 267, August 2005, P52

Josephs, J, (1967), “The Physics of Musical Sound”, Canada, D. Van Nostrand Company

Pierce, J, (1910). “The science of musical sound”, USA, Scientific American Books

Penfold R.A., (1991), Preamplifier and Filter Circuits, Reading: Bernard Babani

Penfold R.A., (1994), Practical Electronic Musical Effects Units, Reading: Bernard Babani

Perkins, Jamie, (n.d.), “The Guitar”, online, Available, http://www.musicianshop.com/Guitar_history.htm, (5th April 2006)

Scranton Academic, “Blues Music”, online, Available, http://academic.scranton.edu/student/PENDRAKS2/page2.html, (10th April 2006)

Topaktas, Bogak, (2005), “Tube Screamer’s Secret”, online, Available, www.bteaudio.com/articles/TSS/TSS.html, (9th December 2005)

Wampler, B, (n.d.), “How to Build Your Own Effects Pedals (A step by step guide), Brian Wampler

Wikipedia, (n.d.), Grunge Music, online, Available, http://en.wikipedia.org/wiki/Grunge_music, (9th December 2005)

Weinstein, Deena., (1991), Heavy Metal (A cultural Sociology), New York, Lexington Books

Young, E (1979) “The New Penguin Dictionary of Electronics”, Middlesex, Penguin Books Ltd