DISTORTION

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ABSTRACT

This work attempts to introduce the technology and the science behind non-linear effects focusing on Distorted guitar effects. A short history of Distortion and its impact on modern music is followed by physical theories and modeling techniques (Clipping, Harmonic Distortion, N-order Volterra serries) in non-linear domain. We briefly go through Simple circuits and approaches to analogue Distortion (Diode Clipping) afterwards.

Basics of different approaches to designing digital Distortion (Wave-shaping, Simulation of analogue circuits) construct the final part of this review.

1. INTRODUCTION

Distortion effects create "warm", "dirty" and "fuzzy" sounds by compressing the peaks of a musical instrument's sound wave and adding overtones. The three principal types of distortion effects are overdrive, distortion and fuzz. Distortion effects are sometimes called “gain” effects, as distorted guitar sounds were first achieved by over-driving tube amplifiers. Distortion has long been integral to the sound of rock and roll music, and is important to other music genres such as electric blues and jazz.

The terms “distortion”, “overdrive” and “fuzz” are often used interchangeably, but they have subtle differences in meaning. Overdrive effects are the mildest of the three, producing "warm" overtones at quieter volumes and harsher distortion as gain is increased. A "distortion" effect produces approximately the same amount of distortion at any volume, and its sound alterations are much more pronounced and intense. A fuzzbox (or “fuzz box”) alters an audio signal until it is nearly a square wave and adds complex overtones by way of a frequency multiplier.

Distortion can be produced by effects pedals, rackmounts, pre-amplifiers, power amplifiers, speakers and more recently, digital amplifier modeling devices and software [1].

1.1. History

The first amplifiers built for electric guitar were relatively low-fidelity, and would often produce distortion when their volume (gain) was increased beyond their design limit or if they sustained minor damage. One of the earliest recorded examples of distortion in rock music is the 1951 Ike Turner and the Kings of Rhythm song "Rocket 88", on which guitarist Willie Kizart used an amplifier that had been slightly damaged in transport. In the early 1950s, pioneering rock guitarist Willie Johnson of Howlin' Wolf began deliberately increasing gain beyond its intended levels to produce "warm" distorted sounds. Chuck Berry's 1955 classic "Maybellene" features a guitar solo with warm overtones created by his small valve amplifier.

By the mid 1950s rock guitarists began intentionally "doctoring" amplifiers and speakers in order to create even harsher distortion. In 1956 guitarist Paul Burlison of the Johnny Burnette Trio deliberately dislodged a vacuum tube in his amplifier to record "The Train Kept A-Rollin” after a reviewer raved about the sound Burlison’s damaged amplifier produced during a live performance. Guitarist Link Wray began intentionally manipulating his amplifiers' vacuum tubes to create a “noisy" and “dirty” sound for his solos after a similarly accidental discovery. Wray also poked holes in his speaker cones with pencils to further distort his tone. The resultant sound can be heard on his highly influential 1958 instrumental, "Rumble".

In 1961, the American instrumental rock band The Ventures asked their friend session musician and electronics enthusiast Orville "Red" Rhodes for help recreating the “fuzz” sound caused by a faulty preamplifier on Grady Martin’s guitar track for the Marty Robbins song "Don't Worry". Rhodes offered The Ventures a fuzzbox he had made, which they used to record "2000 Pound Bee" in 1962. The first purpose-designed commercial distortion circuit was the Maestro "Fuzz Tone" Model FZ-1, released in 1962.

In 1962 the American instrumental rock band The Ventures recorded "2000 Pound Bee" using the first fuzzbox.

Distortion gained widespread popularity after guitarist Dave Davies of The Kinks used a razor blade to slash his speaker cones for their 1964 single "You Really Got Me". In 1966, Jim Marshall of the British company Marshall Amplification began modifying the electronic circuitry of his amplifiers so as to achieve a "brighter, louder" sound and fuller distortion capabilities.

In May 1965 Keith Richards used a Gibson Maestro Fuzz-Tone to record "(I Can't Get No) Satisfaction". The song's success greatly boosted sales of the device, and all available stock sold out by the end of 1965. Early fuzzboxes include the Mosrite FuzzRITE and Arbiter Group Fuzz Face used by Jimi Hendrix, the Electro-Harmonix Big Muff Pi used by Hendrix and Carlos Santana, and the Vox Tone Bender used by Paul McCartney on "Think for Yourself" and other Beatles recordings.

In the late 1960s and early 1970s hard rock bands such as Deep Purple, Led Zeppelin and Black Sabbath forged what would eventually become the heavy metal sound through a combined use of high volumes and heavy distortion [1].

1.2. Clipping

In the context of music amplification distortion is equated with clipping.

When an amplifier is pushed to create a signal with more power than its power supply can produce, it will amplify the signal only up to its maximum capacity, at which point the signal can be amplified no further. As the signal simply "cuts" or "clips" at the maximum capacity of the amplifier, the signal is said to be "clipping". The extra signal which is beyond the capability of the amplifier is simply cut off, resulting in a sine wave becoming a distorted square-wave-type waveform [1][6].

Amplifiers have voltage, current and thermal limits. Clipping may occur due to limitations in the power supply or the output stage. Some amplifiers are able to deliver peak power without clipping for short durations before energy stored in the power supply is depleted or the amplifier begins to overheat [6]. Because the clipped waveform has more area underneath it than the smaller maximum unclipped waveform, the amplifier produces more output power. (See the waveform to the right for an example.) This extra power can cause damage to loudspeaker components, including the woofer, tweeter, or crossover, via overheating [6].

In the frequency domain, clipping produces harmonics at higher frequencies than the unclipped signal. This additional high frequency energy has the potential to damage a loudspeaker's tweeter via overheating [6].

Music, which is, clipped experiences amplitude compression, whereby all notes begin to sound equally loud because loud notes are being clipped to the same output level as softer notes [6].

Solid-state amplifiers have a reputation for harsh sounding distortion. This makes sense when you consider the design of the typical solid-state power amplifier. In order to achieve maximum power output, decent efficiency, and keep coast low, solid-state amplifiers are often built using combinations of op amps and/or discrete transistors that drive a class AB output stage [7].

A class AB push-pull stage will exhibit symmetrical hard clipping when over-driven. *Hard clipping* means that there is a sharp discontinuity where peaks of the output signal faltten out. This causes the output to contain high amplitude odd harmonics, which sound harsh and give the amplifier the infamous “transistor” sound when overdriven [7].

Vacuum tube based amplifiers, particularly those using triodes, tend to exhibit *soft clipping.* This means that the peaks of the output signal flatten out in a smooth, gradual way, reducing the relative amplitude of the higher odd harmonics. In addition tube amps often clip asymmetrically, which introduces even harmonics that sound less raspy and harsh [7].

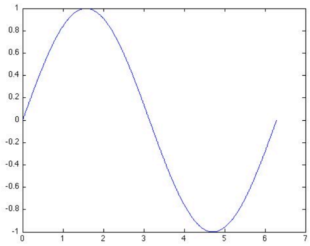

Figure 1. Sine wave

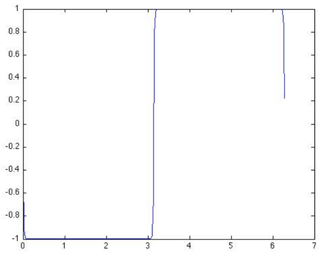

Figure 2. Clipped Sine wave

1.3. Harmonic Distortion

Distortion is any unwanted change that occurs in an audio signal. There are many types of distortion. Distortion can alter the amplitude, alter the phase, or create spurious frequencies that were not present in the input signal. Harmonic distortion is one form of the latter type of distortion.

Harmonic distortion colors the sound, making it unnatural. When it occurs in the signal processing or amplification circuitry, it gives the impression the loudspeakers are breaking up because harmonic distortion is also created when loudspeakers are overdriven. Perhaps most dangerously, harmonic distortion can actually promote premature loudspeaker failure.

As with noise, there are times when distortion is a desired result, mainly in guitar amplifier/speaker systems, where the coloration caused by the distortion becomes part of the sound the musician seeks to create. A special type of signal processor, an exciter, also uses high frequency distortion components to brighten the sound [2].

Harmonic distortion is comprised of one or more signal components that are whole number multiples of the input frequency. For example, if a pure 100 Hz sine wave is applied to the input for a circuit, and the output contains not only 100 Hz, but also 200 Hz, 300 Hz, 400 Hz and 500 Hz signals, the output can be said to contain 2nd, 3rd, 4th and 5th harmonics. These harmonics are distortion, since they were not part of the input signal [2].

Note that the human ear tend to find the odd-order harmonics more objectionable than even order harmonics. Higher order harmonics will tend to be more objectionable than lower order harmonics [2].

Figure 3 and 4 compare the sine wave frequency components before and after being distorted.

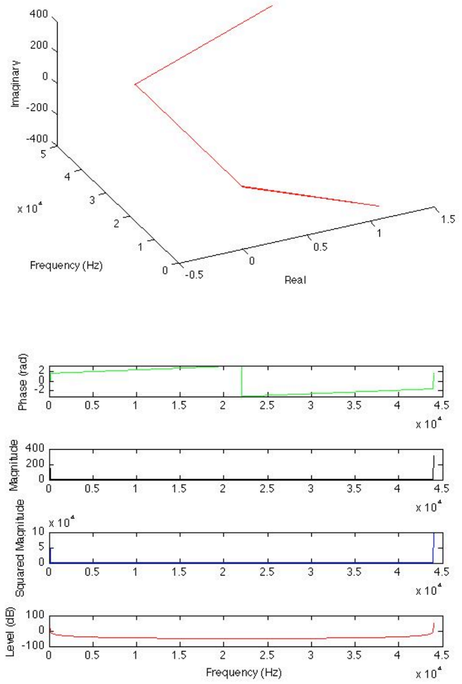

Figure 3. Sine wave FFT (Fast Fourier Transform)

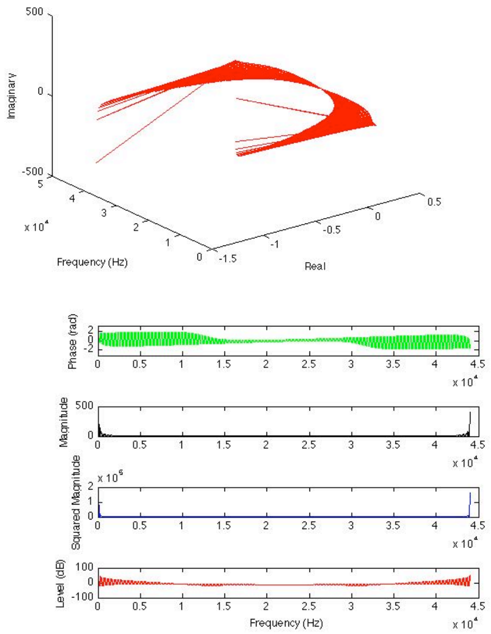

Figure 4. Distorted Sine wave FFT (Fast Fourier Transform), additional high frequency energy visible.

1.4. Nonlinear Processors

There are two approaches towards nonlinear processing for audio applications. The first approach is driven by musical applications of nonlinear effects and the second is driven by the reduction of nonlinear behavior especially in the field of loudspeakers. We cover the first approach of nonlinear effects for musical processing, where topics from nonlinear modeling of physical systems play an important role [3].

1.4.1. Basics of Nonlinear Modeling

Digital signal processing is mainly based on linear time-invariant systems. The assumption of linearity and time invariance is certainly valid for a variety of technical systems, especially for systems where input and output signals are bounded to a specified amplitude range. In fact several analog audio processing devices have nonlinearities like valve amplifiers, analog effect devices, analog tape recorders, loudspeakers and at the end of the chain the human hearing mechanism. A compensation and the simulation of these nonlinearities need nonlinear signal processing and of course a theory of nonlinear systems. From several models for different nonlinear systems discussed in the literature the Volterra series expansion is a suitable approach, because it is an extension of the linear systems theory. Not all technical and physical systems can be described by the Volterra series expansion, especially systems with extreme nonlinearities [3].

A nonlinear system with memory can be represented analytically as a Volterra series. There has been work on forming finite-order Volterra series for simulating electronics (Schattschneider and Zölzer 1999; Abel and Berners 2006; Hèlie 2006). However, these are interesting only for low- order circuits, whereas for highly nonlinear systems, direct simulation by numerical methods is more computationally efficient (Bilbao 2006). Even with many terms, Volterra series, which use polynomial models, do not converge sufficiently for efficient implementation of a clipping nonlinearity with large signal excursions [4].

1.5. Analog guitar effects

Analog guitar distortion effect devices known as *solid-state distortion boxes* commonly include a diode clipper circuit (Figure 7.) with an embedded low- pass filter (Figure 6). These distortion- effect devices can be modeled and accurately simulated as Ordinary Differential Equations (ODEs) [4]. Analog guitar effects, whether based upon vacuum tubes or solid- state devices, consist of circuits that are accurately described in the audio frequency band by nonlinear ODEs [4]. The Boss DS- 1 circuit (Roland Corporation 1980) is a distortion pedal, and its schematic can be approximately divided into blocks as shown in Figure 5 [4].

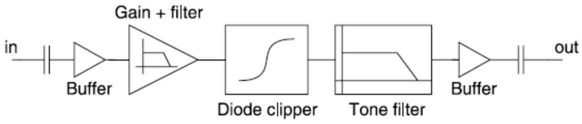

Figure 5. Partitioning scheme and block diagram for the Boss DS- 1 circuit.

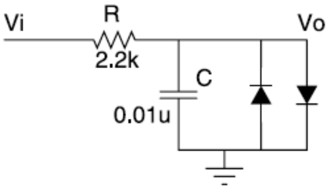

Figure 6. RC low- pass filter with diode limiter.

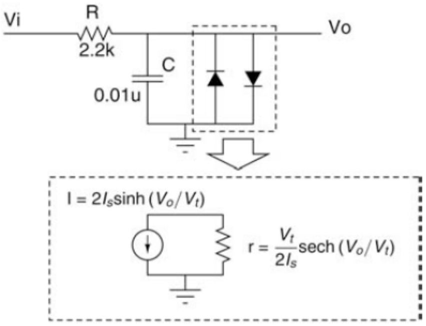

Figure 7. Linearized diode- clipper circuit.

1.6. Digital Distortion

The simplest digital implementations of guitar distortion use a static nonlinearity, borrowing from classical waveshaping synthesis techniques (Arfi b1979; Le Brun 1979). The static nonlinearity is usually a lookup table, or a polynomial (e.g., spline fit) of an arbitrary function that saturates and clips. In the waveshaping technique, Chebyshev polynomials are used as a basis function for this nonlinearity, because they allow the control of individual harmonics when the input signal is a full-amplitude sinusoid (Le Brun 1979). However, Chebyshev polynomials do not model intermodulation of multiple sinusoidal components [4].

Guitarists tend to feel that digital implementations of distortion effects sound inferior to the original analog gear. This work attempts to provide a more accurate simulation of guitar distortion and a physics based method for designing the algorithm according to the virtual analog approach. Often guitar effects are digitized from a high level understanding of the function of the effect [5]. The work in [8] describes the results of a more detailed, physical approach to model guitar distortion. This approach has been adopted previously in the context of generating tube-like guitar distortion, not to model a specific effect as done here. This approach starts with the equations that describe the physics of the circuit and is an alternative to obtaining the static transfer curves of a nonlinear system by measurement [5].

2. CONCLUSION

Non-linear processing is a very broad field of research. With focusing on Distortion this work attempted to cover the basics of technology and science behind the magical distorted guitar sound.

Lower Coast, variety and abundance of Digital effects have made them very popular between guitar players; but in terms of sound there is still the argument of analogue effects being superior. Many of the papers presented in this review have attempted to close the gap between the analogue and digital distortion and the field is still very open.

As the mathematical concepts in non-linear processes are very advanced, a more in depth analysis of distortion requires the study of both modeling and implementation of non-linear processors and amplifiers. If this review has intrigued its audience to do so, then the purpose of this review is fulfilled.

3. REFERENCES

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