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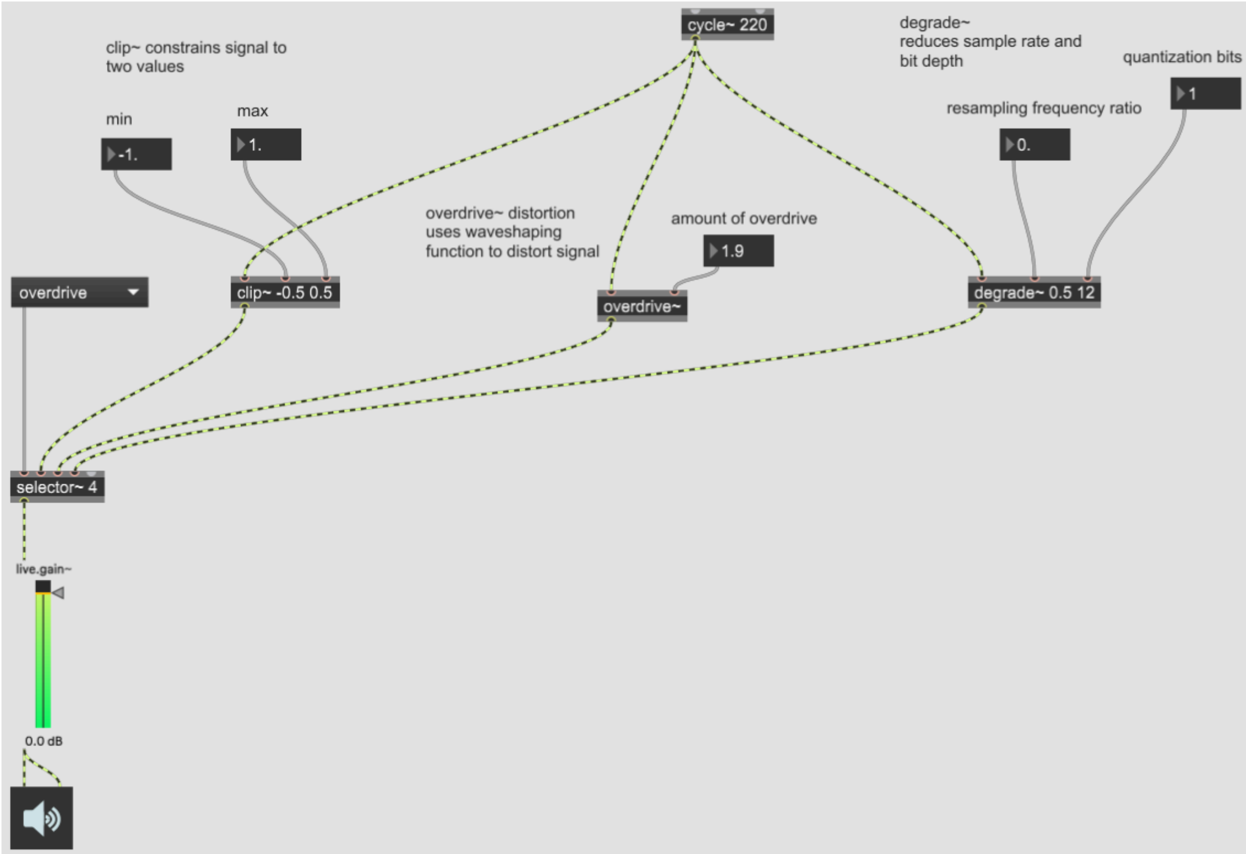
Distortion in Guitar-Centric Genres

Distortion is the intentional or undesired sonic destruction or deformation of an audio signal's original waveform. In music, it is a versatile audio effect that is used extensively across a wide range of music genres. Originating organically in the late 1940s, its popularity and influence on guitar playing has carried pop and rock 'n roll music for decades, which subsequently helped to pioneer newer, heavier-sounding alternative genres toward the close of the twentieth century. Distortion has become an identifying characteristic associated with all types of rock and metal music, both of which consist of a plethora of smaller subgenres supported by countless unique artists and listener communities. For many of these subgenres, distortion serves as the staple lead guitar effect and provides the heavy, raw sound that correlates with the attitudes and emotions expressed by artists within said genre communities. From a technical standpoint, distortion can be simply described as the clipping of an audio signal at some amplitude. When the peaks and troughs of an audio signal are clipped, the waveform and its frequency components are altered, increasing the amount of frequency-varying-sinusoids that make up the new distorted signal. Types of distortion can be categorized in many different ways by the timbre of their sound and signal processing techniques used to achieve them. Generally, distortion is separated into harmonic and inharmonic distortion. This paper discusses these waveshaping methods, provides a history of distortion from its first use in music, and touches on the influence and importance of distortion on the music of today.

Types of Distortion

Harmonic distortion is where the processor enhances the inputted signal as overtones are added. Clipping is an example of harmonic distortion that may have inharmonic components; there is hard clipping where the signal is sliced off, leading to digital distortion, and soft clipping where the signal is slightly compressed to smoothen peaks. Clipping occurs as a result of overmodulation of a signal past the maximum level of an audio system.

Inharmonic distortion is where the processor distorts the inputted signal in a grungy way, where the added components are not related to the inputted signal. Inharmonic distortion occurs with aliasing, where frequencies are higher than the sample rate, and truncation, where bit-depths are reduced without dither (noise) to reduce quantization distortion.



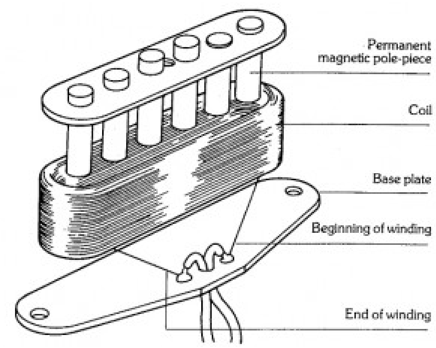
Max8/MSP has a clip~ object that constrains the signal to two values (generally $-1 \leq n \leq 1$). The overdrive~ object uses a waveshaping function to distort a signal, amplifying it with maximum values of ± 1; values outside of the maximum are soft clipped similar to an overdriven tube-based circuit. Max also has a degrade~ object that can distort the signal through aliasing and/or truncation by reducing sample rate (by a ratio) and bit-depth without interpolation or dithering, respectively.

History

Distortion was first discovered by accident around the mid-1940s, as blues and country musicians began to experiment with rock 'n roll-esque music before its popularity in the mid-1950s. Guitar amplifiers at the time were designed to produce clean, dry tones from electric guitars, but when pushed to their limits they could output a dirtier sound that was new to musicians of the era. When turned up to maximum levels, typical vacuum tubes used in analog amplifiers would undergo an overloading effect, resulting in a warm, crunchy sound that musicians quickly gained a liking for. A good example of this technique is exemplified in Bob Wills and his Texas Playboys' "Bob Wills' Boogie," a rock 'n roll tune recorded in 1946. While the distortion is not super pronounced, you can hear the light crunch on the lead guitar, a sound that would quickly catch on in popular music. In addition to playing at high volumes, some musicians also realized that recording with faulty equipment and broken amplifiers could also contribute some distortion to the guitar's sound. Dave Davies, lead guitarist of the rock band The Kinks, admits to slashing the speaker cone on his amplifier with a razor blade to achieve the iconic distortion in The Kinks' 1964 hit "You Really Got Me." A popular example of this is demonstrated in Marty Robbins' 1961 single "Don't Worry," a song that reached number one on Billboard's Hot Country Songs and number three on Billboard's Hot 100. About a minute into the song, the bass guitar features a thick, rattling distortion that was unlike any other guitar tone of the era. The track was recorded through a faulty mixing console that Robbins' producer, Don Law, had kept at his studio for its unique sound. Grady Martin, the bass player, was reluctant to use the effect on the final recording, but Law insisted on including the track; had it not made the final cut, distortion in popular music may have not been the same today. Glenn Snoddy, a session engineer that worked with Don Law, was infatuated with the faulty console and tried his best to replicate it until its amplifier gave out. He partnered with another session engineer at the studio, Revis Hobbs, in an attempt to make a stand-alone distortion unit based on the tone from "Don't Worry," utilizing germanium transistors to achieve the timbre. After reaching a working prototype, Snoddy and Hobbs pitched and sold the design to Gibson, who released the first ever commercially available distortion pedal in 1962: the Maestro Fuzztone.

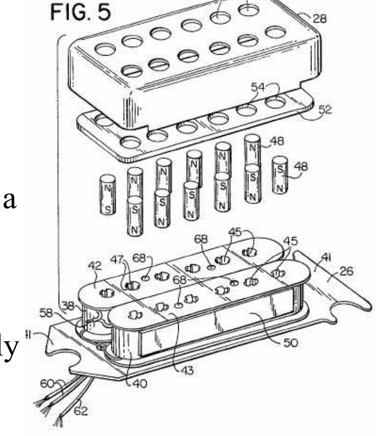
The Fuzztone was originally advertised as a method to mimic the sounds of other instruments, such as low brass, banjo, and cello. However, the pedal had a sound of its own that musicians began to cherish and experiment with. One of the most prominent early examples of the fuzztone in popular music is The Rolling Stones' 1965 hit "(I Can't Get No) Satisfaction." The catchy guitar riff featured throughout the song features the fuzztone's signature buzzy tone, which soon became a hit among other rock artists as well as amateur musicians. Keith Richards, the lead guitarist of The Rolling Stones, admittedly recorded the track as a placeholder for a brass orchestra part that was never recorded. To Richards' dismay, the final cut of the song was released with the fuzz track, but had an enormous impact on rock music throughout the rest of the decade and subsequently the close of the century. Due to its widespread popularity, Gibson was not able to keep up with the demand of the fuzztone, so engineers and enthusiasts took to designing their own variations of distortion and fuzz circuits. The Arbiter Fuzzface was a popular distortion module released in 1966; at a fifth of the price of a Maestro Fuzztone, it was an ideal choice for amateur musicians and touring artists, and became an integral part of legendary guitarist Jimi Hendrix's signature sound. Mike Matthews, electrical engineer and eventual founder of renowned pedal company Electro-harmonix, experimented with several fuzz modules before developing the legendary Big Muff in 1969, manufacturing individual units and selling them out of his shop in New York. The pedals became a quick hit, with artists like Jimi Hendrix, The Beatles, and Carlos Santana using the effect on releases in the same year. The release of these pedals marked a turning point in popular music, inspiring heavier guitar sounds and a universal drive to further experiment with audio effects. Without the loud, gritty distortion made accessible by these distortion modules, genres like hard rock and heavy metal would be completely different or even cease to exist.

Electric Guitars



While most recognizable distortion is conducted by pedals or amplifier dirty-channels, the design of guitar pickups was also changing throughout the 50s and impacting the ways that guitarists played. Before the 1950s, electric guitars typically only featured single coil pickups. A single coil pickup consists of six cylindrical magnets held in place by a plastic fitting that are surrounded by a copper wire coil with several thousand turns, where one end of each magnet is positioned directly below a string on the guitar. When the strings are played, the vibrations create a change in magnetic field around the pickup, inducing a current and voltage into the copper wire coil and creating the electrical signal that is run through the amplifier. Single coil pickups are still widely used today, and are recognizable by their bright, sharp tone. However, a complaint from many musicians at the time was the high pitched buzz or “hum” produced by the pickups, a result of electromagnetic interference from surrounding electronics. Engineers at both Gibson and Gretsch guitars had reached a “humbucker” prototype by the early 1950s, designed to eliminate the undesired hum from electric guitars. The design included the use of two single coil pickups connected in series and out of phase, where one set of magnets was positioned with the north pole facing the strings, and the other set with the south pole facing the strings. When wired correctly, the unwanted buzz would be eradicated from the guitar signal, but the most

FIG. 5

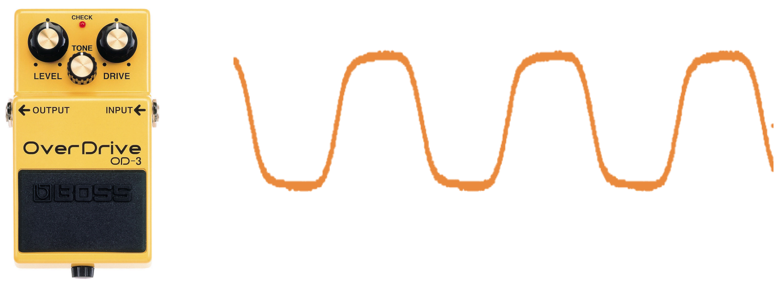


prominent feature of the humbucker is the tone it created. Where single coils were bright and clear, humbuckers provided a darker, fatter sound that guitarists had not been able to experiment with before. Additionally, the use of two pickups caused the humbucker to have a much higher gain output than a single coil pickup, so it was much easier for guitarists to achieve a warm, mild, organic distortion on their guitar sound. The humbucker quickly became prevalent in all rock music from its release, and its wide harmonic spectrum paired with the use of distortion units shaped the heavy guitar tones that defined hard rock and metal through the 70s and 80s.

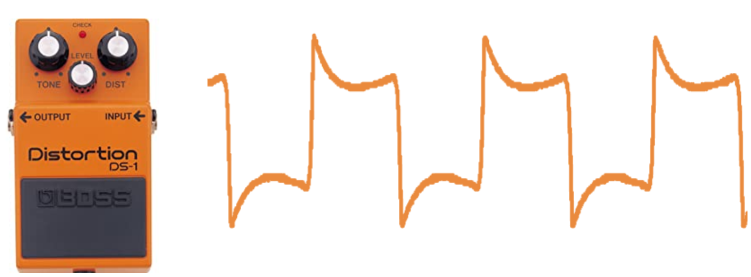
Distortion Pedals

Since their integration into popular music, guitar pedals have become a massive part of guitar playing for professional and amateur guitarists alike. As one of the staple audio effects for guitar, pedals that feature distortion fall into three broad categories: overdrive, distortion, and fuzz. The fundamental difference between the three is simply the level of distorted audio that is included in the output signal, where overdrive features the least amount and fuzz features the most. However, the adjustment knobs on most guitar pedals allow for thorough experimentation that can change a guitar sound from its anticipated titular effect, so these categories mainly define the pedals by their intended application. Below are oscilloscope plots that show the output signal of a sine wave through three popular guitar pedals; the Boss OD-3 Overdrive, Boss DS-1 Distortion, and Dunlop Fuzzface.

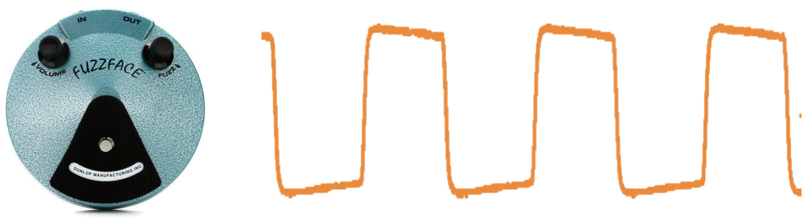
The overdrive pedal presents the least-modified signal of the three, with soft-clipping on the peaks for a mild crunchy sound. While it is closest to the original signal, the added harmonics are made apparent by the tapered peaks, bringing the input slightly closer to a square-esque wave. Overdrive, as its name implies, is mainly intended to simulate the effect of overloading or overdriving an amplifier to reach a natural-sounding slight distortion effect, without overpowering the clean guitar signal.



The distortion pedal output is the most strange looking of the three, featuring two sharp pointed peaks per wavelength. While it strays away from a square-looking sinusoid, its irregular shape demonstrates the versatility of the distortion pedal, its increased number of harmonics, and its ability to create unique sounds that are more powerful than overdrive. Distortion will eliminate most of the clean tone from the guitar, but the sound is still sharp enough to give some expressive freedom to the guitarist, making it very popular for metal genres that emphasize impressive guitar playing.



Fuzz, being the most intense effect of the three, features the most amount of harmonics and pushes the sine wave significantly close to a square wave. As it has the broadest harmonic spectrum, a fuzzed guitar signal has a big, noisy, broken sound, and is used extensively in 90s alternative rock and grunge for rhythm guitar lines. Compared to its relatives, fuzz leaves little room for expression when it comes to stylistic guitar playing, as the signal is almost completely overpowered by its distorted component. While this may seem like a negative trait to some, the aggressive nature of fuzz is fun to experiment with and typically beloved by audio effect enthusiasts.

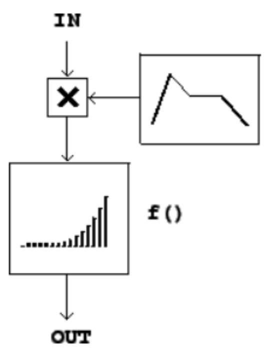


As technology continues to thrive and evolve, digital music equipment is becoming more prevalent throughout synthesis, recording, and effect processes. While most musicians prefer analog sound to digital, the use of digital equipment has revolutionized the availability and versatility of all sorts of audio effects. Due to its ability to naturally round and taper a signal, as well as its extended use throughout rock music, analog distortion is typically preferred by musicians. Computers are at a disadvantage to analog circuits when it comes to waveshaping, as they must digitally recreate the clipped output, where circuit effect modules are simply responding naturally to the applied input signal. However, digital innovations have led to new, unique forms of distortion; one of the most notable types is the bitcrusher. A bitcrusher pedal contains a small computer that takes in an input signal, reduces the sampling rate, and outputs the low resolution signal. This has a glitchy, hazy effect on the guitar, pushing the limits of distortion's definition in musical context. Recent innovations in analog technology has also had a grasp on the audio effect community, discovering new, distinct methods of physically distorting guitar signals. The Plasma Pedal from Gamechanger Audio makes use of a miniature tesla coil to distort the signal; the input signal travels between two electrodes in a xenon-filled tube, converting it into a collection of electric discharges, and reconfigured into an audio signal via an analog rectifier circuit. The pedal uses all analog equipment and creates a full, saturated distortion that can be extensively modulated using each of the pedal knobs. While some may argue this is excessive just for a distortion pedal (especially considering its price of $300), it serves as a fascinating example of how far our understanding of audio electronics has come since the birth of audio effects and experimentation.

From the release of the first distortion modules, the effect has had a tremendous effect on the popular music of today. Had the first fuzz pedals not been released when they were, the history of rock music would be entirely different. Today, 60 years after the release of the Maestro Fuzztone, there is a diverse population of distortion pedals built by hundreds of effects companies around the world. Distortion plays a central role in genres like hard rock, noise, alternative, and every single type of heavy metal. If distortion had not become popular in the mid-60s, its influence likely would not have caught on until years later, which would directly impact the rise of heavy metal in the mid-70s. While it can be broken up into over twenty different subgenres, distortion is one of the main characteristics that every subgenre has in common. As popular music can and will always influence future popular music, the chain reaction of distortion-inspiration through the close of the twentieth century will forever leave its mark on guitar playing across all genres of popular music.

Intermodulation Distortion

Intermodulation distortion, or IMD, is the production of new output signals created from the nonlinear combination of two or more input signals. Demonstrating IMD requires understanding of waveshaping, the process of passing it through a nonlinear function $f()$, distorting the signal to a different shape.



Given a transfer function where the input is squared,

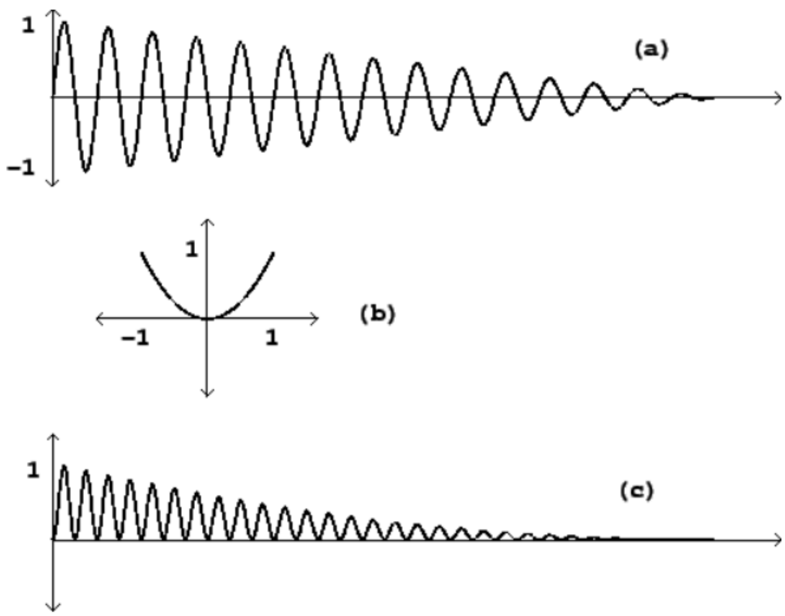
$$f(x) = x^2,$$

with a sinusoidal input

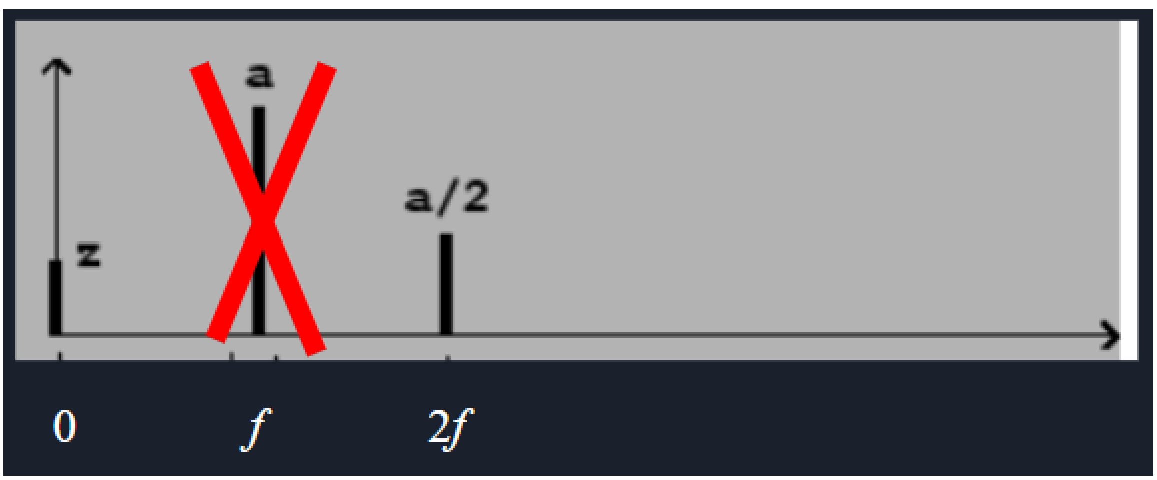
$$x[n] = acos(\omega n + \varphi),$$

the result of this waveshaping is

$$f(x[n]) = \frac{1}{2}a^2(1 + cos(2\omega n + 2\varphi)).$$



If a equals 1, this is essentially **ring modulation** of two sinusoids of the same frequency, resulting in two sinusoids, one of 0 frequency and one of twice the original, except the output is proportional to the square of the input. In addition, the carrier frequency is *not* present.



For IMD, maintaining

$$f(x) = x^2$$

and inputting **a combination of two sinusoids**,

$$x[n] = acos(\alpha n) + bcos(\beta n),$$

where α and β are the *angular frequencies* of each of the two sinusoids, the result is

$$f(x[n]) = \frac{1}{2}a^2(1 + cos(2\alpha n)) + \frac{1}{2}b^2(1 + cos(2\beta n))$$

$$+ ab[cos((\alpha + \beta)n) + cos((\alpha - \beta)n)].$$

This is equivalent to

$$f(p + q) = p^2 + 2pq + q^2,$$

where $p = acos(\alpha n)$ and $q = bcos(\beta n)$ using the trigonometric identity:

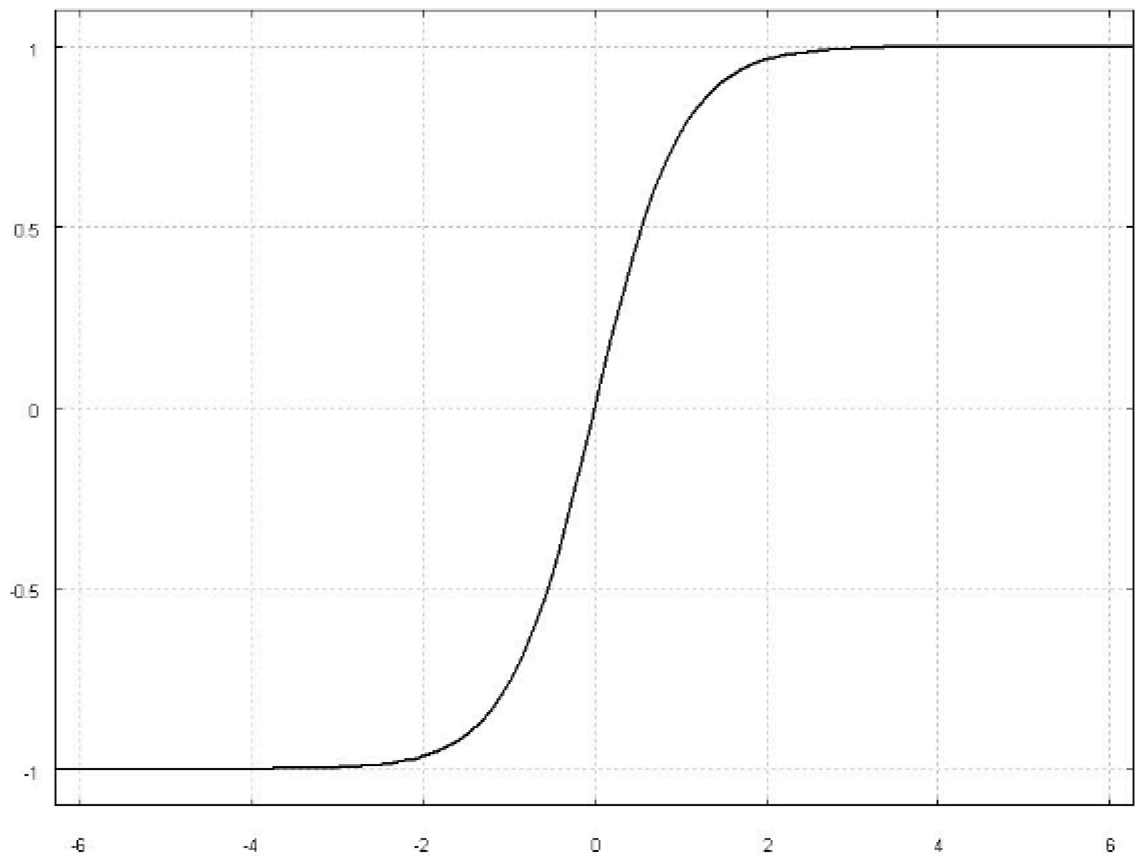
$$cos^2 x = \frac{1 + cos(2x)}{2}$$

p^2 and q^2 are the results of sending the two sinusoids individually through $f(x) = x^2$, so $2pq$ is the term that is created from this intermodulation. Given k sinusoids, there are k terms in the sinusoidal combination and there are $\frac{1}{2}(k^2 - k)$ intermodulation terms. Using this example, $k = 2$ sinusoids, meaning $\frac{1}{2}((2)^2 - 2) = 1$ intermodulation term.

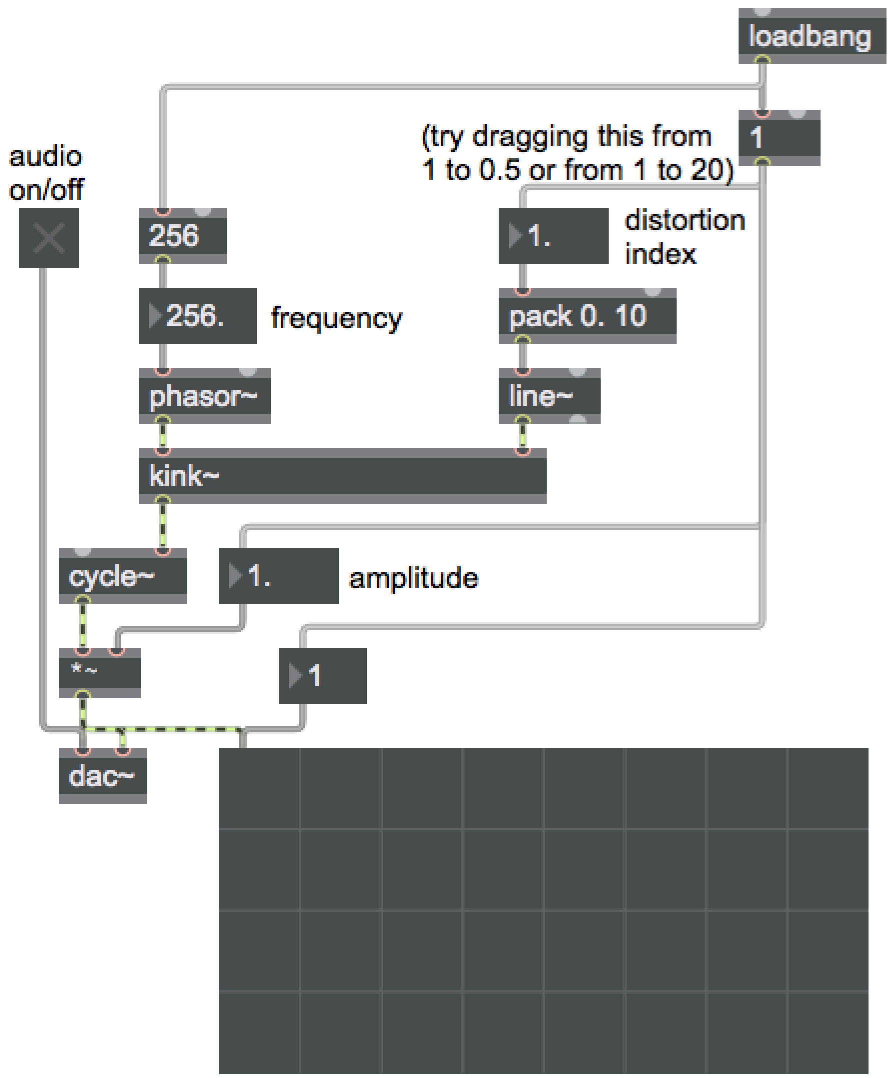
Intermodulation distortion is why playing 3rds, 6ths, 7ths, 9ths, etc. sound bad when there is a lot of distortion present. This means that, while an electric guitar player could play two parts at the same time, it may be necessary for them to play one part and another player play the other due to the intermodulation distortion that may be present. This could also be fixed with tuning, depending on what the player needs.

Distortion Synthesis Methods

Waveshaping is one of many distortion synthesis methods. The aforementioned intermodulation distortion example was an example of polynomial waveshaping, that is, waveshaping with a polynomial transfer function ($f(x) = x^2$). Polynomials generally produce a bandlimited matching spectrum for sinusoids, but may produce unnatural sounds at the partials for time-varying spectra. Therefore, many other transfer functions may be used, most commonly the **hyperbolic tangent function**, or tanh. The signal is clipped and there is a smooth transition between the negative and positive outputs. In Max, this can be demonstrated using the tanh~ object. The tanh transfer function is displayed below.



The second common distortion synthesis method is Frequency Modulation (FM) synthesis, where the amplitude of a transmitted signal, or modulator, modulates the instantaneous frequency of a carrier signal. FM synthesis was founded by John Chowning and was patented by himself and Yamaha in the 1970s to 90s. Phase Distortion (PD) synthesis is paired with FM, where dynamic changes in sync, or phase, of the signal introduce harmonic distortion and create a sound with a dynamic timbre. PD is known for its use in Casio synthesizers in the 1980s. PD synthesis is demonstrated below.



Variants of FM synthesis have been found, including Asymmetrical FM synthesis, where the original FM result is ring-modulated by an exponentiated signal, and Modified FM synthesis (ModFM), where the formula for FM is modified by changing complex numbers and mapping them to real ones (represented with the ℜ symbol).

The equation for Asymmetrical FM synthesis is

$$s(t) =$$

$$exp(0.5k(r - \frac{1}{r})cos(\omega_m))sin(\omega_c + 0.5k(r + \frac{1}{r})sin(\omega_m)) =$$

$$\sum_{n=-\infty}^{\infty} r^n J(k) sin(\omega_c + n\omega_m).$$

An FM equation expressed with complex exponential terms is

$$s(t) = cos[\omega_c t + zcos(\omega_m t)] = \Re\{e^{i\omega_c t + izcos(\omega_m t)}\}.$$

Applying a change of variable $z = -ik$,

$$s(t) = \Re\{e^{i\omega_c t + kcos(\omega_m t)}\} = e^{kcos(\omega_m t)} cos(\omega_c t),$$

which when multiplied by by the normalization factor $exp(-k)$, is the basic Modified FM synthesis formula.

The third method is the use of Discrete Summation Formulas/ae (DSF), where summations are used to produce a certain wave shape.

A common DSF is

$$s(t) = \sum_{k=0}^{N} a^k sin(\omega + k\theta)$$

which is used for bandlimited signals.

Conclusion

Distortion is key in digital music, as an unpleasant and pleasant feature of audio. The striking distortion of electric guitars have become the most important part of many music genres, such as rock and metal. It has proven to become more complex as years go on, as many different types of distortion have emerged, as well as different synthesis methods, and new techniques for distortion continue to be developed to this day using a variety of different mathematical and acoustical ideas.

Distortion has had many important figures during its development, in popular music for the public, instrument/equipment engineering, and its electronic/digital research. This has allowed for distortion to impact communities, musically and culturally. This audio effect, as displeasing as it is in loud bands, and as gratifying as it is in today's developing popular music world, will always be key to music's evolution, and will perhaps be a stepping stone for another musical discovery to come.

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