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PAPER

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The warm, rich sound of valve guitar amplifiers

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Abstract

Practical solid state diodes and transistors have made glass valve technology nearly obsolete. Nevertheless, valves survive largely because electric guitar players much prefer the sound of valve amplifiers to the sound of transistor amplifiers. This paper discusses the introductory-level physics behind that preference. Overdriving an amplifier adds harmonics to an input sound. While a moderately overdriven valve amplifier produces strong even harmonics that enhance a sound, an overdriven transistor amplifier creates strong odd harmonics that can cause dissonance. The functioning of a triode valve explains its creation of even and odd harmonics. Music production software enables the examination of both the wave shape and the harmonic content of amplified sounds.

Introduction

Compact, lightweight, inexpensive, low-energy, and reliable solid state diodes and transistors have made glass two-element rectifier valves and three-element amplifier valves nearly obsolete. In fact, valves are now manufactured in only three countries, Russia, China, and Slovakia. And why does the old technology survive? Because most electric guitar players much prefer the sound of valve amplifiers! In the collection of popular guitar amps in figure 1, a single exception stands out. Jazz guitar players generally seek a clean undistorted sound they can achieve with all the practical advantages of transistor amps. But rock and popular guitarist players usually prefer warm, rich, overdriven sounds, and valve amps best produce such sounds.

How do valve amps produce their much sought-after sound? There is a prevailing answer among musicians: when overdriven, valves tend to produce even harmonics that add pleasant complexity to sound, while transistors tend to produce odd harmonics that can cause dissonance. But this answer only raises more questions. Do experiments support the even/odd harmonics claim? Why do even harmonics enrich a musical sound, and why can odd harmonics compromise a sound? How do valves shape waves, and how do wave shapes imply the presence of even and odd harmonics? Why does the timbre of the sound from a valve amp change when a guitar is played more loudly? As this paper discusses, some basic physics plus a knowledge of triode valve function provide the background needed to answer all of these questions.

Examining amplifier output

Most popular guitar amplifiers are in fact two amplifiers in series. The first, the so-called preamp, changes the timbre of an incoming sound by adding harmonics to that sound when valves are overdriven. The relatively low-voltage signal output by the preamp is then input to the power amp, which amplifies its weak input to produce a signal with voltage sufficient to drive a speaker.

Figure 1. Some popular guitar amplifiers.

Power amp valves can additionally add harmonic content to a sound if they are overdriven.

Figure 2 shows two small guitar amps. The Fender Pro Jr amp on the left combines a preamp using two small ECC83 double triode valves (also known as 12AX7 tubes) with a power amp using two EL84 pentode valves. The Bugera BC15 amplifier [1] on the right combines a single ECC83 preamp valve with a transistor power amp. Both the simplicity of its preamp and its hybrid design make this inexpensive amp ideal for studying valve and solid state wave shaping.

Logic Pro X [2] is Apple's comprehensive music production program. GarageBand software [3, 4], bundled with all Apple computers, is a simplified version of Logic. With both programs, it is possible to observe in real time the frequencies that comprise a sound using a spectral analyzer within software equalizers and to view the shapes of sound waves recorded in audio files with file editors. Figure 3 shows Logic displaying the output from an overdriven valve that follows the input of a pure sine wave. The top graph, displaying relative loudness in dB units versus frequency in Hz units, is a so-called frequency domain plot. (Fast analyzer response comes at the cost of peak broadening. Each peak in fact represents a single precise frequency.)

Figure 2. Fender Pro Jr valve amp on the left. Bugera BC15 hybrid amp on the right.

The bottom graph, displaying wave shape as a relative voltage versus time in seconds, is a so-called time domain plot.

I applied the amplifier overdrive test shown schematically in figure 4 to both the valve preamp and the transistor power amp of a Bugera BC15 amplifier. Through the amp's guitar cable jack, I input a 200 Hz sine wave generated by Audacity [5].

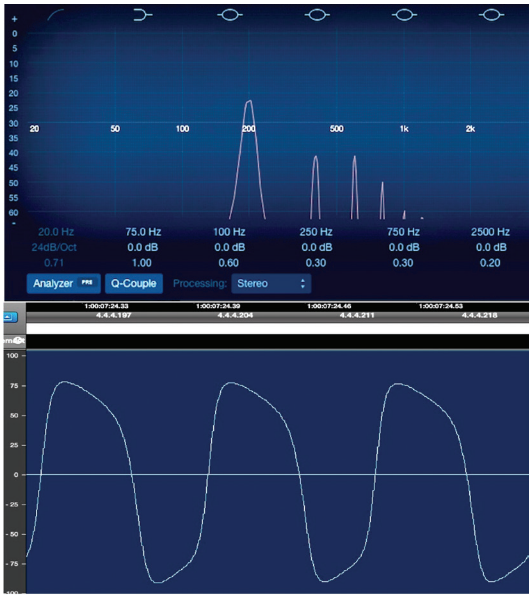

Figure 3. Amplifier output displayed by Logic. Top in frequency domain, bottom in time domain.

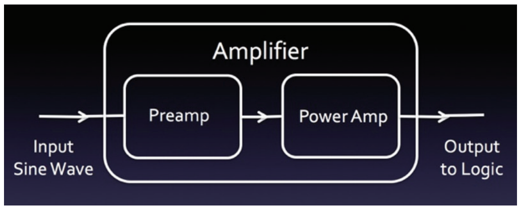

Figure 4. Amplifier overdrive test: input a sine wave, increase preamp or power amp gain, and view frequencies or wave shape using Logic.

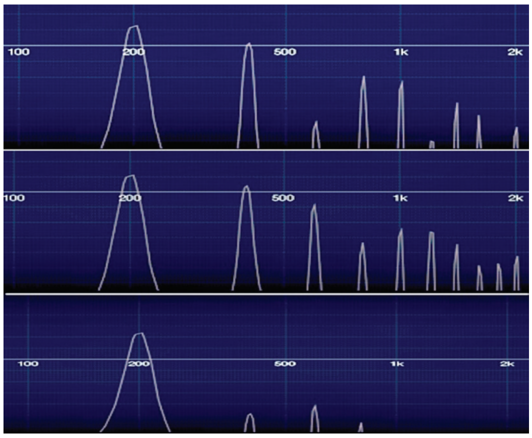

Figure 5. Output from a Bugera BC15 amplifier. Top: moderately overdriven preamp valve; middle: strongly overdriven preamp valve; bottom: weakly overdriven transistor power amp.

With the 'master' knob that controls power amp gain set low, I steadily increased the preamp's gain by turning the 'gain' nob. Then with the gain knob set low, I gradually turned up the master knob setting. Both times I observed output frequencies using the spectral analyzer in Logic and recorded the output of the amplifier to audio files so I could observe wave shapes.

Observed output frequencies

Are experimental output frequencies consistent with the expectations of even and odd harmonics for a valve preamp and a transistor power amp? As the frequency domain plots in figure 5 show, the answer is yes, but with some qualification. These plots clearly show that overdriving a preamp or power amp produces harmonics whose frequencies are even and odd integer multiples of the 200 Hz input frequency. The top plot for the moderately overdriven valve preamp shows prominent 2nd and 4th harmonics at 400 and 800 Hz and only a very weak 3rd harmonic at 600 Hz. But the story is not quite so simple. The 5th harmonic at 1 kHz is quite strong, while the 6th harmonic at 1.2 kHz is very weak. As the middle plot shows, when preamp gain is increased, the odd 3rd harmonic strengthens while the even 4th harmonic weakens. This shift from even toward odd harmonics at increasing gain is a general characteristic of valve amplifiers that further explains their appeal. An electric guitar player can overdrive an amplifier two ways, by turning up the amp's gain control, and by attacking guitar strings more strongly, thus increasing the strength of the input signal to the amp. An experienced electric guitar player knows how to 'play the amplifier'. Just strike the strings harder, and timbre changes along with volume. Consistent with expectations, the bottom plot shows that a weakly overdriven transistor produces a 3rd harmonic stronger than the 2nd and 4th harmonics.

Pleasant even harmonics and sometimes unpleasant odd harmonics

As the amplifier overdrive test shows, at least at moderate gain, valve amplifiers add even harmonics to a sound more prominently than they add odd harmonics. But why are even harmonics

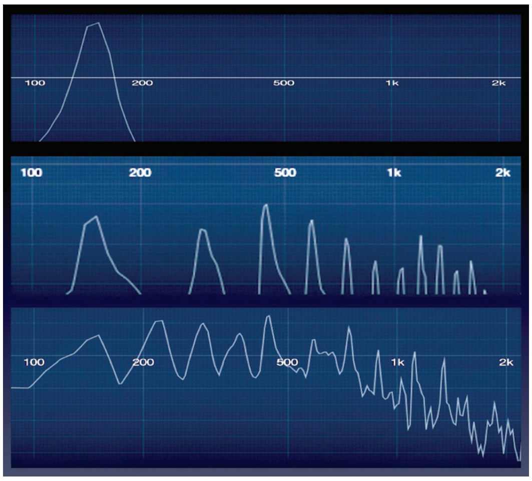

Figure 6. Frequencies output by an amplifier that is not overdriven. Top to bottom: pure D tone, plucked D string, D chord.

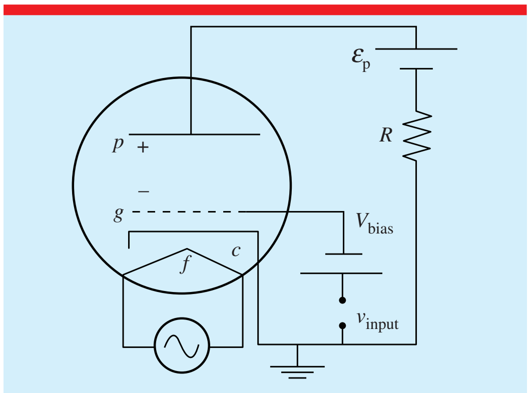

Figure 7. A triode valve functioning as a voltage amplifier.

generally preferable to odd harmonics? Start with an amplifier that is not overdriven. Figure 6 show the frequencies output when a pure tone and the sounds of a plucked guitar string and a guitar chord are input. Few would dispute that the sequential increase in spectral complexity produces fuller and pleasanter sounds. But overdriving a guitar amplifier adds harmonics to *each* of the harmonics shown.

Some music theory is in order here. Consider a Cmaj7 chord constructed from pure C, E, G, and B tones, which are the 1st, 3rd, 5th, and 7th notes of a C major diatonic scale. Additionally, assume that the diatonic scale is a so-called 'just' scale. This means that the frequencies of the 3rd and 5th notes of the scale are the 1st note's frequency multiplied respectively by 5/4 and 3/2 [6]. (There exist many subtly different scales. For example, pianos are tuned to a so-called 'tempered' scale. One simple rule defines tempered tuning: the frequency ratio for any two adjacent piano keys is $2^{1/12}$.)

For simplicity, assume that a tone's strongest even harmonic is its 2nd harmonic and its strongest odd harmonic is its 3rd harmonic. Doubling the frequency of any tone produces a new tone one octave higher than the original tone. Tones an octave apart don't clash with each other. Instead, such tones add warmth and pleasant complexity to a sound.

Now add 3rd harmonics to the notes of the original Cmaj7 chord. Tripling the frequency of any note produces a new note one octave and a 5th higher than the original. For example, the 3rd harmonic of a C note is a G note more than an octave above the original C. Adding 3rd harmonics to each note of the original chord produces new G, B, D, and F$^{\#}$ notes. While the first three new notes, each found in a C major diatonic scale, enrich the original sound, the F$^{\#}$ that is not in this scale adds dissonance. Now imagine the effect of adding unwanted tones to *each* of the frequencies in the guitar chord in figure 6! In brief, second harmonics make a sound richer and fuller, but third harmonics can create dissonance.

The triode valve as an amplifier

So why does a triode amplifier valve produce even harmonics when it is moderately overdriven and odd harmonics when it is overdriven further? The answer begins with the question of how a triode valve converts a varying low voltage signal from an electric guitar into a varying high voltage signal.

Figure 7 is a schematic diagram of a triode valve functioning as an amplifier. A filament *f*, a cathode *c*, a grid *g*, and a plate *p* (also known as an anode) are contained within an evacuated glass enclosure. The cathode ejects electrons when it is heated by the nearby filament. A high-voltage DC emf source $\mathcal{E}_p$ is placed in the cathode-plate circuit to provide a large current (by definition the plate current i_p) from the cathode to the plate.

The grid, a mesh near the cathode, controls the flow of electrons from the cathode to the plate. The grid is at all times kept at a negative potential relative to the cathode by a constant DC bias voltage V_{bias} placed into the cathode-grid circuit. It is to this circuit that the weak variable signal from a guitar's electromagnetic pickups is input. As the guitar input makes the grid's potential more or less negative, the flow of electrons to the plate respectively decreases or increases.

Now apply Kirchoff's loop law to the cathode-plate circuit:

$$\mathcal{E}_{\text{p}} = v_{\text{p}} + i_{\text{p}}R, \tag{1}$$

so that

$$v_{\text{p}} = \mathcal{E}_{\text{p}} - i_{\text{p}}R, \tag{2}$$

where v_{p} is the so-called plate voltage, the plate's potential relative to the cathode's potential and the voltage that drives the speaker. Because the negative grid is near to the cathode, i_{p} decreases substantially if the grid voltage v_{g} becomes slightly more negative. From equation (2), this makes v_{p} increase substantially. Similarly, making v_{g} slightly less negative causes a large increase in i_{p} and a large decrease in v_{p}. In brief, small variations in v_{g} cause large variations in v_{p}. It is through this mechanism that the triode valve functions as a voltage amplifier.

Define a valve's amplification factor α by

$$\alpha = -\Delta v_{\text{p}}/\Delta v_{\text{g}}. \tag{3}$$

If the valve's amplification is linear, i.e. if Δv_{p} and Δv_{g} are directly proportional, the valve makes a sound louder without changing its timbre. However, 'coloring' a sound through the addition of harmonics requires *nonlinear* amplification. Guitar amplifier handbooks provide detailed discussions of valve function and guitar amplifier construction [7, 8]. Many guitar amplifiers include either mechanical or digital reverberation units [9] to simulate the ambience of a large space.

Shaping waves by overdriving a triode valve

A triode valve's plate current i_{p} can reach limits in two distinct ways. If the grid voltage v_{g} becomes sufficiently negative, i_{p} approaches zero, a minimum known as the cutoff current.

On the other hand, if v_{g} becomes insufficiently negative to keep the plate from stripping away electrons as fast as the cathode ejects them,

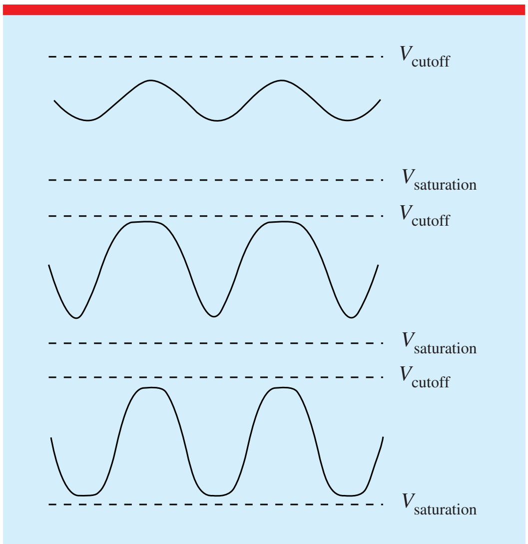

Figure 8. Expected output wave shapes when a sine wave of increasing amplitude is input to the cathode-grid circuit. Top: linear amplification before either plate voltage limit is reached; middle: an asymmetric wave as one plate voltage limit is approached; bottom: a symmetric wave as the second limit is approached.

i_{p} approaches a maximum known as the saturation current $i_{\text{saturation}}$. Consequently, according to equation (2), the valve's plate voltage v_{p} has two fixed limiting values, a cutoff limit

$$V_{\text{cutoff}} = \mathcal{E}_{\text{p}} \tag{4}$$

and a saturation limit

$$V_{\text{saturation}} = \mathcal{E}_{\text{p}} - i_{\text{saturation}}R. \tag{5}$$

Figure 8 shows the expected wave shapes of the output from a triode valve when a sine wave of increasing amplitude is input. The top v versus t graph shows the shape of the output wave before either plate voltage limit is reached. Like the input, the output is a pure sine wave. In other words, the input is linearly amplified without harmonic enhancement. The middle graph shows the top of the wave becoming flattened, or in other words, clipped, as the amplitude of the input wave is increased so that one plate voltage limit is approached. As the bottom graph shows, the bottom of the input wave is also clipped when input amplitude is increased further and the second plate voltage limit is approached.

With increasing input gain, a first harmonic is initially augmented by prominent even harmonics, then odd harmonics begin to dominate

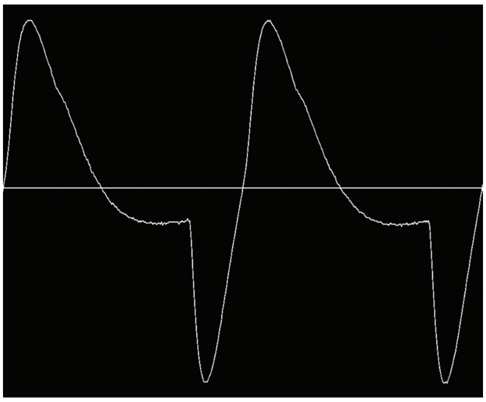

Figure 9. Output wave shape from a Bugera BC15 amplifier with its valve preamp overdriven.

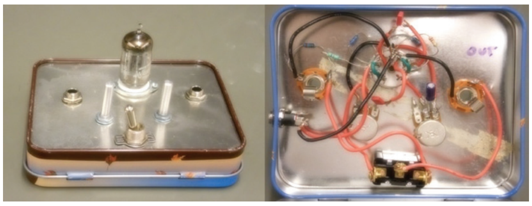

Figure 10. ValveLiTzer© overdrive pedal.

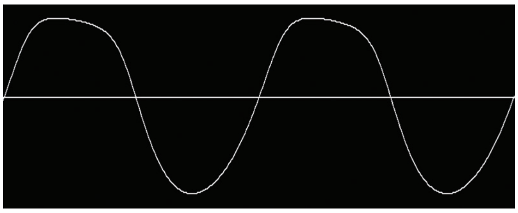

Figure 11. Wave shape output by ValveLiTzer© overdrive pedal.

even harmonics. But how does wave shaping by a valve explain this response? The answer lies in the symmetry of the wave output by a triode valve. As the term is used in discussions of guitar amplifiers, a wave is symmetric if you can invert it (i.e. replace each instantaneous voltage by the negative of that voltage), translate it along the time axis by one-half of a period, and obtain the original wave. By this definition, in figure 8 the bottom wave is symmetric and the middle wave is asymmetric. It can be show that in general, symmetric waves contain only odd harmonics while asymmetric waves contain at least some even harmonics. As two examples, the asymmetric middle wave is in fact a plot of the function

$$v(t) = \sin \omega t + 0.25 \cos 2\omega t, \tag{6}$$

a simple sum of 1st and 2nd harmonics. If you keep increasing the amplitude of the input wave, the bottom wave approaches a square wave, whose Fourier series

$$v(t) = \sin\ \omega t + (\sin\ 3\omega t)/3 + (\sin\ 5\omega t)/5 + \dots \tag{7}$$

is the sum of only odd harmonics [10].

Observing output wave shapes

If you observe wave shapes by recording output sounds as audio files and examine those files in detail by using the audio editor in Logic or GarageBand, you might be as surprised as I was when I saw the output (figure 9) from the moderately overdriven valve preamp of the Bugera BC15 guitar amplifier. Because I instead expected a wave shape resembling the middle plot in figure 8, I called technical support at Bugera to explain my problem. The representative assured me that because my wave was asymmetric, the amp was functioning properly. But then, what explains the strange observed wave shape? There's much more to a valve amp than valves, as online schematic diagrams of popular amps show [11]. It occurred to me that post-valve electronics perhaps changed the phases of some valve output harmonics before they reached the amp's speaker. To check this hypothesis, I ran the amplifier overdrive test on a very simple valve overdrive pedal that one of my students built from a schematic he found online [12].

As figure 10 shows, this pedal employs few electronic components that could potentially shift the phase of harmonics. Figure 11 displays the this pedal's output wave. Not only does the shape of this wave conform to expectations for a moderately overdriven valve, but also, the asymmetry of the wave is consistent with the pedal's warm, pleasant, overdriven sound.

Summary

The signal leaving an electric guitar is already rich in harmonic content, and an overdriven guitar amplifier adds harmonics to each of the original harmonics. While adding even harmonics enhances a sound by adding octave tones, adding odd harmonics produce tones that can clash with the original sound. Music production software enables the examination of sound waves in both the frequency and time domains. Tests conveniently performed in an introductory physics laboratory support the frequently made claim that overdriven valve amps preferentially add even harmonics to sounds while overdriven transistor amps preferentially add odd harmonics.

The analysis of the function of a triode amplifier valve predicts the effect of increasing the strength of the electric signal input from a guitar's pickups upon output wave shape. Wave shape then reveals harmonic content. The asymmetry that results from moderately overdriving a valve indicates the presence of even harmonics, while the symmetry resulting from very strongly overdriving a valve shows the presence of only odd harmonics. At low input signal strength, a sine wave is linearly amplified without harmonic enrichment. As the strength of the input signal increases, a valve first adds even harmonics and then adds odd harmonics.

The art of amplifier design combines musical esthetics with physical principles. Moderately overdriving a valve amplifier produces the warm, complex, and highly listenable sound that electric guitar players enthusiastically seek.

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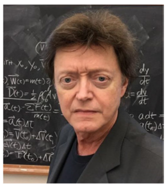

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