Vacuum Tube Triode Nonlinearity as Part of The Electric Guitar Sound

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ABSTRACT

For many years manufacturers have attempted, with varying degrees of success, to market solid state amplifiers for use with the electric guitar. To this day the majority of electric guitarists continue to use vacuum tube amplifiers. Some of the most popular amplifiers used by today's guitarists are old designs, or are copies of some of the old tube amplifier designs.

Inspection of the circuit diagrams of many of the most popular electric guitar amplifiers reveals the presence of a common preamplifier stage, namely a class A triode amplifier directly coupled to a cathode follower. In this paper we examine the distortion characteristics of this configuration. It is shown that grid limiting of both the positive and negative sides of the guitar waveform is responsible for the desirability of this configuration for use in electric guitar amplification.

1.0 INTRODUCTION

This paper focuses on the effect of vacuum-tube amplifiers on the quality of the electric guitar's output signal. In this application the amplifier is frequently operated under overload conditions, and the distortion due to the overload is part of the sound the guitarist hears. Thus the distortion of the amplifier must be considered as part of the electric guitar's sound.

Cabot [1] discusses the minimum audible perception levels of various types of nonlinear distortion. Hussey and Haigler [2] discuss the perceptive differences of tube and solid state guitar amplifiers at sub-overload signal levels. The following sections of this paper examine the effects of the vacuum-tube guitar amplifier distortion at levels of overload much greater than these references [l, 2] intended to address. It is demonstrated that vacuum-tube amplifiers have desirable intermodulation distortion effects in electric guitar applications.

1.1 Background

The electric guitar became popular as a musical instrument in the latter part of the 40's and the early 50's. At this time the transistor had not yet been developed, and the only amplifiers which were available used vacuum tube amplification stages. The early electric guitar pioneers learned how to use the amplifier's characteristics as part of the instrument's sound. The wide dynamic range of the electric guitar causes overload at one or more of the amplifier's stages. The nonlinearity due to these overload conditions has to be considered when characterizing the electric guitar's signal.

When solid-state amplifiers became available most applications quickly switched to their use, due to such factors as lower cost and an extended region of linear operation. The guitar amplifier manufacturers discovered that the guitar players continued to favor vacuum tube amplifiers, and many of the solid-state guitar amplifiers were removed from product lines. To this day, a large number of guitarists use vacuum-tube amplifiers.

This paper examines the nature of the distortion characteristics of vacuum tube guitar amplifiers. In particular it examines two circuit configurations which are responsible for distortion introduction in a large number of guitar amplifier designs. The distortion characteristics of these two triode circuits are related to their effects on the guitar output signal.

Hamm [3] examined the harmonic distortion characteristics of several solid-state and vacuum-tube preamplifier stages under overload conditions. His experiments used single-tone sine-wave test signals, and his paper does not discuss the intermodulation distortion differences between the amplifiers. He demonstrated that vacuum-tube amplifiers under overload conditions cause a shift in the duty cycle of the output signal. Where the. input sine wave is positive during exactly half of its period and negative during the other half, the distorted output waveform has less than half of its period on one side of zero and more than half of its period on the other side. For sine-wave inputs this duty-cycle shift results in more even-harmonic distortion components than solid-state amplifiers, which have a symmetric duty cycle in their distorted output waveforms.

In this paper we focus on intermodulation distortion as an important factor influencing the popularity of vacuum tube amplifiers in electric guitar amplifier applications.

1.2 Overview

Section 2 focuses on the nature of the electric guitar as a signal source. The signal decomposition approach shown in Figure 1 is introduced to simplify the discussions of intermodulation distortion effects on the output signal of an electric guitar amplifier. The concepts of soft limiting and hard limiting are introduced, and it is shown that hard limiting causes an undesirable type of intermodulation distortion which adversely affects the output sound quality.

Section 3 examines the characteristics of two vacuum-tube triode preamplifier circuit configurations which are used in many electric guitar amplifier designs. It is experimentally demonstrated, using triangle wave responses under overload conditions, that the degree of acceptability of a guitar amplifier stage is dependent on how much of the circuit's transient operation is in a hard-limit region. Solid-state amplifiers have most of their overload operation in a hard-limit region. Even under heavy overload conditions, vacuum-tube triode amplifiers have much of their overload operation in a soft-limit region. This is a major reason why guitarists prefer vacuum-tube amplifiers.

Section 4 examines the characteristics of grid current flow in a triode. Grid limiting occurs when the grid circuit becomes forward biased, causing a grid current flow induced voltage drop across the grid circuit source resistance. This is a soft-limiting effect which has no parallel in most solid-state amplifier designs. An approximate analysis of the grid-limiting effect is presented, and the power-function grid limit curves, shown in Figure 11, are described.

Section 5 summarizes the paper's conclusions.

2.0 ELECTRIC GUITAR AS A SIGNAL SOURCE

This paper focuses on the electric guitarist's use of an amplifier as a required part of creating the instrument's sounds. An electric guitar employs an electromagnetic pickup coil, which directly transduces the motion of the metal strings suspended above the pickup into an electric voltage. Since these pickups typically have high source impedances (> 5000 ohms) and have 100 Kohm potentiometers in their tone and volume control circuits, they require a high input impedance in the first preamplifier stage (typically 1 megohm is used).

The only amplifiers which were available in the early years of electric guitar playing had vacuum-tube amplifier stages. Many of the electric guitar amplifiers designed during the decade of the 50's, are easily overdriven by guitar signals. The overdrive effect produces a characteristic distortion. Manufacturers diminished the distortion by adding more feedback, by increasing the supply voltages, and by more carefully balancing the relative signal levels among the amplification stages. Some guitarists continue to insist on using the older amplifiers. Some of the newer tube amplifier designs are patterned after the old amplifiers.

Many guitar players have learned how to use amplifier overdrive distortion as part of the sound they get from their instruments. In this section we discuss some of the characteristics of the electric guitar as a signal source. The effects of amplifier nonlinearity are included in this characterization of an electric guitar signal, since the distorted signal is what the electric guitarist hears while playing. During recording sessions vacuum tube amplifiers are often included in the electric guitar signal paths.

2.1 Dynamic Range and Level Characteristics

The strings of an electric guitar are closely coupled to a magnetic pickup, which responds to the complete range of string movements. Measurements show that the smallest controllable peak output level produced by gently picking a single string is less than .0001 volts. The maximum level obtainable by strongly strumming all six strings is greater than 1 volt. Thus the dynamic range of an electric guitar is greater than 80 dB. A typical peak output level is about 100 millivolts.

Since the guitarist wants to be heard, the level at the output of the amplifier is often adjusted to be high, especially during the solo passages. The newer tube amplifiers have volume controls after the distortion producing stage. Thus there can be large amounts of overdrive distortion even at moderate listening levels with some amplifiers.

2.2 Overdrive Used for Sustain

Although the electric guitar has a wide dynamic range, the instrument does not possess the ability to produce a long sustain on a single note. Guitarists have wanted to be able to produce enough sustain to sound more like a saxophone soloist. Guitarists learned to use amplifier overdrive to increase the sustain of their solo notes. While the amplifier is in overdrive, the output level stays relatively constant, until the input signal decays to the level of linear operation. This overdrive-induced sustain has become a regular part of the electric guitar sound, and the nature of the overdrive sound quality varies greatly among different amplifier designs.

2.3 Multiple Notes Passed Through Distortion

Each string of the guitar contributes to the output signal. The waveform from each string has its own harmonic structure. Since a guitar has six individually controlled strings, up to six complex tonal waveforms are mixed together in the pickup's output. The guitar also allows for bending notes by stretching one or more of the strings. Thus at any given time the guitar signal may consist of several independently decaying waveforms, with no direct harmonic relationships.

Linear analysis can be used when the superposition of input waveforms results in a superposition of the outputs that would result from each input waveform alone. Amplifier nonlinearities cause superposition-based analysis to fail. The concept of signal spectrum comes from linear analysis. The output spectrum is often used to characterize the nonlinear distortion components of a pure sine wave passed through an amplifier. This output spectrum is used to define the well-known harmonic distortion measurement. However, when input signals with a complex spectrum pass through nonlinear amplifiers, harmonic distortion measurements provide no help in inferring the spectrum of the output waveforms.

The major perceptual differences between tube and solid-state amplifier distortion are manifest when multiple tones pass through at the same time. While two different amplifiers may sound similar when a single string is plucked on a guitar, they often will sound strikingly different when multiple strings are strummed. Different amplifiers may have similar harmonic distortion characteristics, but their intermodulation distortion effects may differ greatly. These intermodulation distortion effects are important for the acceptability of guitar amplifiers.

2.4 Nonlinear Distortion as Part of the Electric Guitar Signal

To simplify discussion of intermodulation distortion effects, we introduce a signal-decomposition approach. The typical output of an electric guitar has a predominant waveform shape, upon which is superimposed a smaller additional waveform. A simplified example is shown in Figure 1.

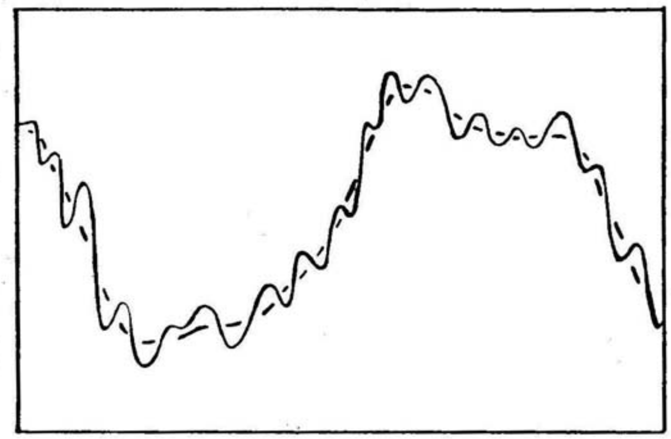

Figure 1 - Electric guitar signal decomposition approach. The modulating waveform is indicated by the dashed curve. The total signal is composed of the sum of the modulating waveform and a small riding waveform.

The predominant waveform shape is typically caused by the signal of the lower-frequency string which has the most energy, and the added waveforms come from harmonics of the high energy string as well as the waveforms from the less energetic strings. The term *modulatinq waveform* refers to the part of the overall signal which causes overload, and the term *riding waveform* describes the wiggles that ride on top of the modulating waveform.

The total input signal consists of the sum of the modulating waveform and the riding waveform.

The most pleasant sounding amplifiers tend to have a very smooth and continuous transition from linear operation into overdrive. These preferred amplifiers avoid reaching a hard cutoff limit. Hard limiting occurs when an amplifier has an incremental gain of zero. For small-amplitude riding waveforms, the incremental gain is predominantly a function of the modulating waveform level, and it can be used to infer the effect a riding waveform will have on the output waveform. For a linear system the incremental gain is always equal to the absolute gain.

All amplifiers have zero incremental gain during some portion of an input modulating waveform at sufficiently high overload levels. A riding waveform mixed in with the modulating waveform can not get through when the modulating waveform induces a hard-limit condition. Soft-limiting tube amplifiers, which are sought after for their pleasing sound, let the small waveforms from each string through during more portions of the modulating waveform (i.e., there is less hard limiting).

With these preferred tube amplifiers, at pleasant levels of overdrive distortion hard limiting is hardly ever reached. This can be seen by inspecting oscilloscope traces of guitar amplifier input and output signals. This is a predominant reason for the wide acceptance of certain guitar amplifier designs.

The next section examines the distortion characteristics of two common circuit configurations found in many of the popular guitar amplifier designs.

3.0 TRIODE DISTORTION MECHANISMS

3.1 General Triode Characteristics

The characteristic curves for vacuum-tube triodes are all similar to those displayed in Figure 2. Each curve corresponds to a constant value of grid-to-cathode voltage (Vgk), and shows how the plate current (Ip) varies with the plate-to-cathode voltage (Vpk). The characteristics of this triode show that the device operates in the positive grid voltage region, with no major discontinuities.

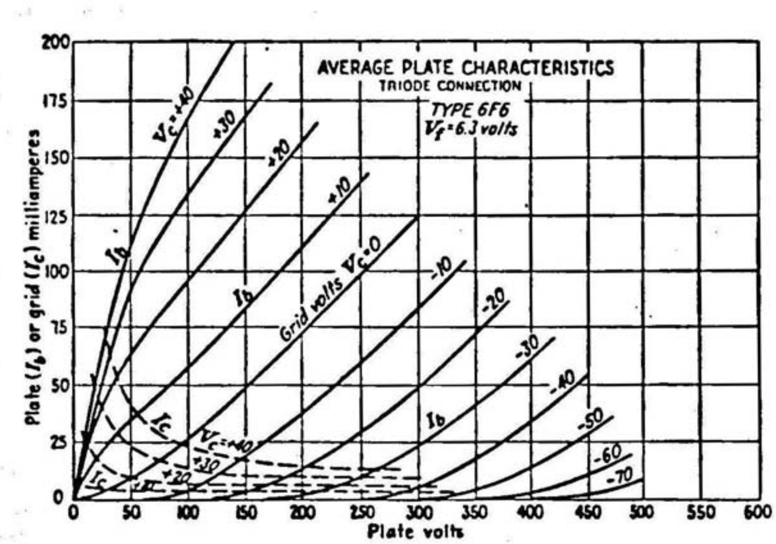

Figure 2 - Vacuum triode characteristic curves, (Spangenberg 1948)

Note that the spacing between the curves is not uniform, and that they get closer together as the plate current decreases. Thus there is a variation of the linearized tube parameters with plate current, as shown in Figure 3. The vaccuum tube triode does not have as wide a linear region as a bipolar transistor. In this paper we are concerned with amplifier operation under overdrive conditions.

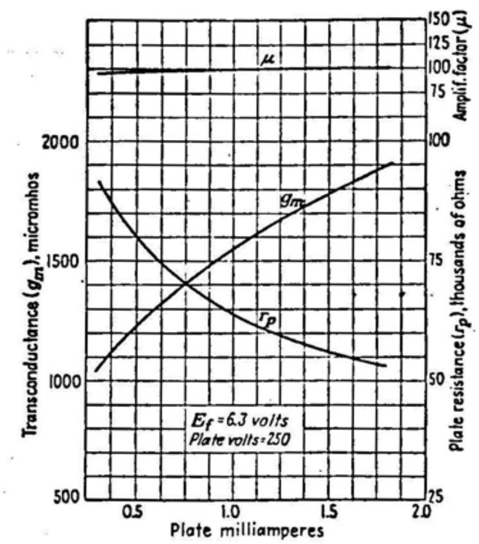

Figure 3 - Variation of 6F6 tube parameters with plate current. (Spangenberg 1948)

The distortion characteristics of an amplifier depend on the total circuit design, not just the type of electronic device used. The usual approach taken to analyze an electronic circuit is to superimpose a load line on the electronic device's characteristic curves, which shows the constraints of operation that the circuit places on the device. The load-line approach works for circuits which have all their nonlinearities confined to the electronic device.

3.2 Class A Triode Amplifier Distortion

A popular triode used in many guitar amplifiers today is the 12AX7. Its characteristic curves are shown in Figure 4, along with a 100K ohm load line and a 440 volt supply voltage. This load line corresponds to the circuit in Figure 5, which is a class A ac coupled triode preamplifier stage. We can use this circuit diagram and Figure 4 to discuss the typical distortion mechanisms which occur in a class A tube triode amplifier. Overload caused by each side of the modulating waveform occurs at either end of the load line.

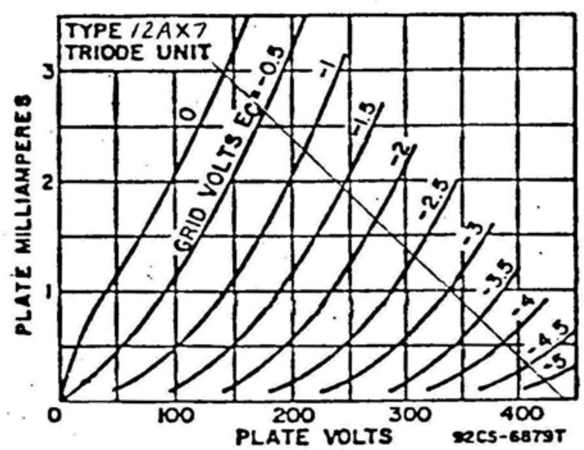

Figure 4 - 12AX7 triode plate current characteristics. with load line for circuit in Fig. 5. (RCA Tube Manual)

The lower end of the load line shown in Figure 4 (Ip = 0, Vpk = 400 volts), corresponds to the condition known as plate cutoff. This is a hard limit, since any changes in grid voltage will not change the plate current while in cutoff. Notice that the transition into plate cutoff is gradual, causing a decrease of the triode transconductance gm , as shown in Figure 3. Triode plate cutoff is similar to transistor cutoff, although a transistor has a less gradual transition into the hard limit. A transistor's current amplification factor is more constant near cutoff. Riding waveforms are not allowed to get through the amplifier when the modulating waveform has caused transition into a hard limit condition.

At the upper end of the load line we reach a condition known as grid limiting. Grid limiting happens when the grid circuit becomes forward biased and begins to conduct current. As the input voltage to the circuit is made larger, the grid current increases, causing an increased voltage drop across the source resistance. This tends to make the grid voltage increase much less than the input. Grid limiting is a soft limiting effect, since at all times the grid voltage will continue to change in response to changing input voltage, no matter how far into overdrive the grid is driven. At the same time the amplifier output current continues to be controlled by the grid-to-cathode voltage, as seen by looking at Figure 2.

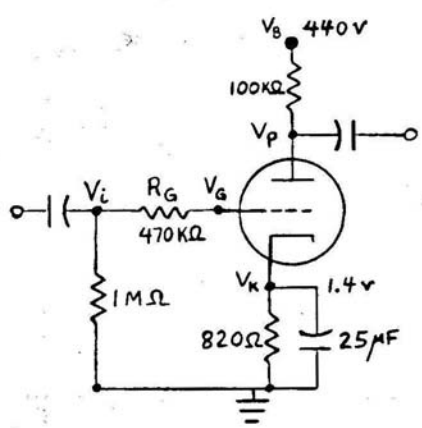

Figure 5 - Class A 12AX7 triode amplifier.

The grid-limiting mechanism has no parallel in transistor amplifiers. Collector saturation is the opposite limiting effect to cutoff in transistor amplifiers. Saturation in a bipolar transistor is a condition with both junctions forward biased, leaving the output current controlled by the supply voltage and the total load-line resistance. Collector saturation is a hard-limiting effect. Thus bipolar-transistor amplifiers, including op amps, have hard-limiting effects on both sides of the modulating waveform.

The class A triode stage has a hard limit on only one side of the modulating waveform. The soft-limiting effect on the other side is a predominant factor in the acceptance of tube amplifiers by guitarists.

3.3 DC-coupled Cathode Follower Stage

A common circuit found in many popular guitar amplifiers is shown in Figure 6. The class A triode stage from Figure 5 is DC coupled to a cathode follower stage. The output impedance of the plate circuit of the first stage is the input impedance of the cathode-follower stage.

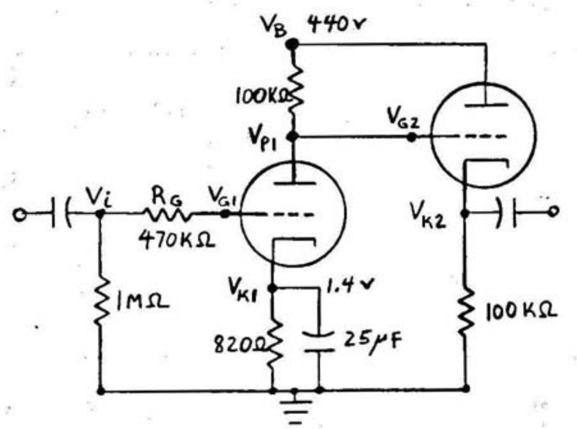

Figure 6 - Class A triode stage with DC coupled cathode follower stage.

The exact nature of the cathode-follower stage's grid current characteristic is difficult to analyze. .The cathode follower has a large amount of negative feedback; an increase in grid-to-cathode voltage results in an increase in plate current, which causes the cathode voltage to increase, causing in turn a decrease in grid-to-cathode voltage. The cathode voltage is always slightly higher than the grid voltage, and the grid-to-cathode voltage is close to zero and negative in value. In this mode of operation the grid current is positive and controlled primarily by the plate to cathode voltage. The dashed curves in Figure 2 show grid current characteristics for constant Vgk values.

As the cathode voltage increases, the plate-to-cathode voltage Vpk decreases. A decreasing plate voltage allows more of the electrons flowing past the grid to be drawn into the grid, since they are accelerated less by the plate potential. The resultant grid current flow causes a voltage drop through the output impedance of the preceding class A stage. This produces a soft limiting effect, until the plate of the class A stage reaches its hard cutoff limit.

The additional soft limiting of this side of the input voltage waveform increases the symmetry of the distortion. At input levels small enough to avoid plate cutoff this system provides a soft limiting characteristic for both sides of the input waveform. This is a major factor responsible for this circuit's favorable distortion effects.

3.4 Triangle Wave Response Characterization of Distortion

It is convenient to look at low frequency triangle waveform responses to infer amplifier distortion characteristics. The triangle wave responses shown in Figures 7 - 9 were obtained by connecting a triangle waveform to one input of a dual-trace oscilloscope, and the output waveform to the other oscilloscope input. The gain of one of the oscilloscope input amplifiers was adjusted so the two waveforms coincided on the display at low signal levels. Successively increasing the level of the input waveform, and adjusting the vertical position of the input wave trace to match the output near the center of the wave, led to the triangle responses shown in Figures 7, 8 and 9.

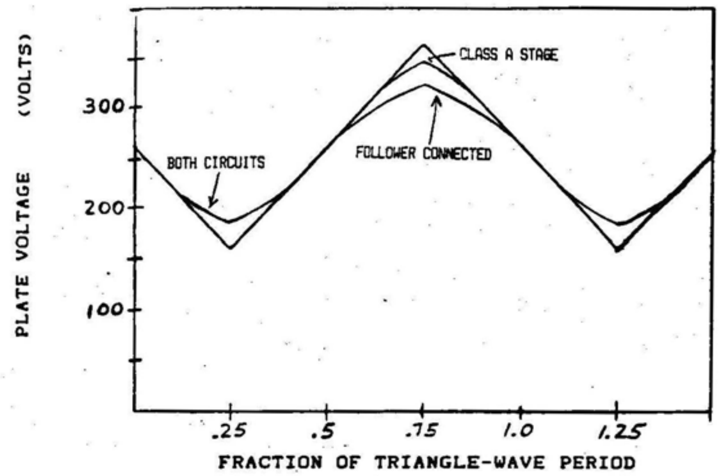

Figure 7 Triangle-wave response, slight overload. Plate voltages for circuits in Fig. 5 and 6 are shown along with scaled and shifted input triangle wave. In first half cycle both waveforms are identical. In second half cycle the plate voltage Vpl in Fig. 6 circuit is smaller than the plate voltage Vp in Fig. 5 circuit due to grid current flow in cathode follower.

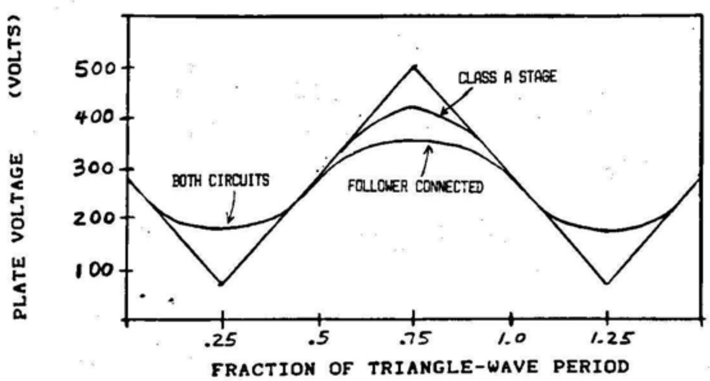

Figure 8 - Triangle-wave response, moderate overload. Plate voltages for circuits in Fig. 5 and 6 are shown along with scaled and shifted input triangle wave. In second half cycle the plate voltage in Fig. 6 is less than that in Fig. 5 due to cathode follower grid-current flow.

The triangle-wave frequency chosen was 100 Hz. Higher frequency input waves are affected by the large Miller-effect capacitance at the grid, coupled with the large grid source resistance Rg. The resulting RC time constant causes linear phase distortion for triangle wave frequencies greater than 100 Hz. The break frequency for this time constant is close to 1000 Hz, and often guitar amplifiers have a compensation capacitor in parallel with Rg to extend the high frequency response. The test circuit had no compensation capacitor installed.

The triangle response of a class A stage in extreme overload is shown as one of the curve* in Figure 9. This response is for the circuit in Figure 3. Note the sharper transition and flatness of the cutoff region of the response, compared to the smooth transition and softness of the grid limit region.

In the class A triode stage triangle response, there is a difference in the character of the plate waveform in the grid-limit region and in the plate-cutoff region. Notice that the slope of the waveform never becomes completely horizontal in the grid-limit region, but that it is totally flat in a large portion of the plate-cutoff region. There is also a duty-cycle shift of the output wave relative to the input as the voltage levels increase. This duty-cycle shift is caused by the DC offset shift of the grid input circuit due to grid-waveform asymmetry.

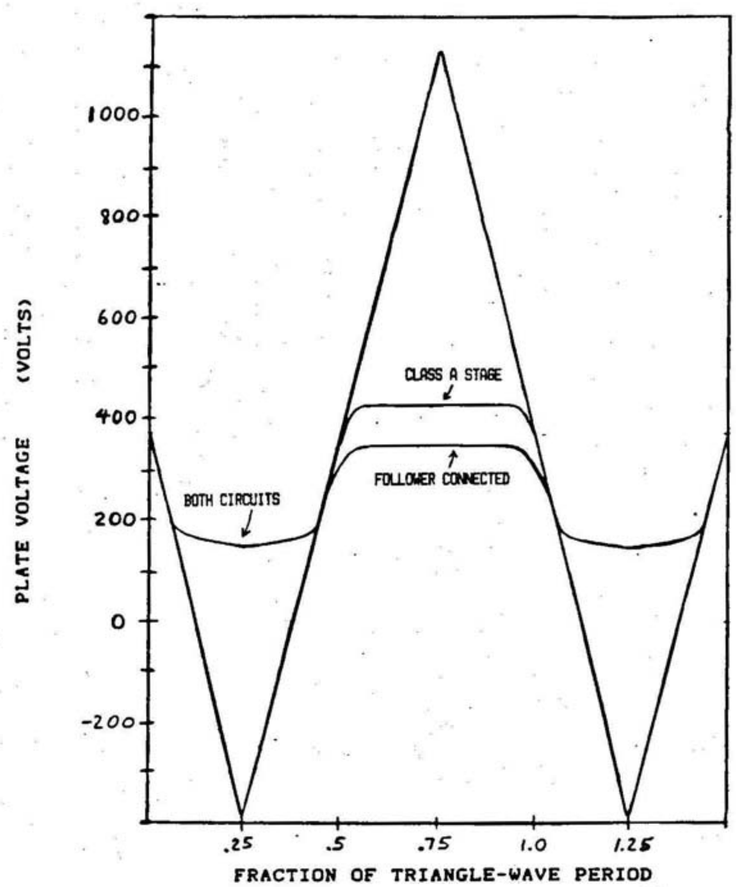

Figure 9 Triangle-wave response, heavy overload. Plate voltages for circuits in Fig. 5 and 6 are shown along with scaled and shifted input triangle wave. In second half cycle the plate voltage in Fig. 6 is less than that in Fig. 5 due to cathode follower grid-current flow. Note duty cycle shift due to rectification of input wave, and hard limited plate voltage in second half cycle.

Notice that the duty cycle of the distorted triangle wave in Figure 9 is greater for the cutoff side than for the grid-limiting side. Triode amplifiers have a duty-cycle shift as the signal is driven into overload. It is this duty cycle shift which is responsible for the predominance of even harmonic distortion components when driven by a sine wave. A rectangular waveform which has a duty cycle of exactly 50% has no even harmonic components [7].

Transistor amplifiers are usually biased for symmetric distortion to maximize output level, and as a result produce predominantly odd harmonic distortion components when driven by a sine wave. Transistor amplifiers can be designed to produce even harmonic distortion by shifting their bias points, but they still will not sound like vacuum-tube amplifiers. Transistor amplifiers in overdrive always have hard limiting on both sides of the modulating waveform.

The following subsections discuss what happens as the level of a symmetric triangle wave increases at the input of the circuits in Figures 5 and 6. They refer to the triangle responses in Figures 7 - 9.

3.4.1 DC Bias Operation

With no input signal, the DC voltage at the input side of the grid source resistor Rg is close to ground potential. The reverse-bias grid current does cause a small positive voltage across the input resistor Ri in Figure 5, but this is negligible for the voltages shown. The cathode voltage is 1.4 volts DC, and the plate voltage is 265 volts DC.

The cathode follower stage doesn't change the bias conditions of the class A stage. The grid voltage of the cathode follower is the same as the plate voltage of the preceding stage. The cathode voltage of the second stage is slightly higher than its grid voltage. The cathode voltage is always slightly higher than the grid voltage in all regions of the cathode follower's operation (within a range of 1 to 2 volts).

3.4.2 Small Input Levels

For small input signals, the positive peak of the triangle wave is well below the bias voltage at the cathode of the class A stage, keeping the grid circuit reverse biased. The amplifier is linear in this region of its operation, and has a voltage gain of 75.

For small input levels the cathode follower stage tracks the amplified input voltage of the class A stage closely, with no distortion effects.

3.4.3 Beginnings of Overload

As the positive peak of the input triangle wave gets closer to the cathode-bias voltage, the grid circuit starts to become forward biased. As the grid-to-cathode voltage Vgk increases, the grid current increases, which increases the voltage drop across Rg. In this region of operation the grid voltage no longer tracks the input voltage, and grid limiting takes effect. Since the tube is predominantly in its linear region of amplification, the AC plate voltage is an amplified copy of the inverted AC grid voltage, with a very small amount of plate distortion. This is shown in the upper curve in Figure 7.

For the DC coupled cathode-follower amplifier, two types of distortion come into play as the plate voltage of the class A stage increases. Long before the plate-cutoff distortion takes affect in the first stage, grid current begins to flow in the cathode follower stage, as discussed in Section 3.3. This causes a grid-limiting distortion effect for the opposite side of the modulating waveform to that grid limited by the first stage. This is the region of operation which produces the most desirable limiting effect. This can be seen in the lower curve of Figure 7.

3.4.4 Duty-cycle Shift Begins

As the grid voltage waveform becomes asymmetric due to grid-limit distortion in the input circuit, a DC shift is introduced at the grid. This grid-limiting induced downward shift of the input wave causes an upward shift in the peak value of the plate voltage waveform. The class A stage is driven toward plate cutoff by this input circuit DC shift. This is shown in Figure 8. Note that hard limiting has not yet been reached.

By the time the level is reached at which significant DC shift occurs in the input circuit of the AC coupled class A stage, the grid limit distortion of the cathode follower has already become significant.

3.4.5 Plate Cutoff is Reached

When the peak value of the plate voltage waveform approaches the supply voltage, plate cutoff begins to take effect. Eventually a hard limit is reached by the plate voltage. This can be seen in both curves in Figure 9. When in plate cutoff the input circuit still has a decreasing DC level with increasing input signal level, causing even more of the plate voltage waveform to be pushed into cutoff. This shift in input DC level is responsible for the duty-cycle shift of the output waveform while it is in plate cutoff.

When the plate of the first stage reaches the hard cutoff limit, the cathode follower output is also hard limited. The grid limit distortion of the cathode follower squashes the overloaded signal, as can be seen in Figure 9.

3.5 Reasons for Acceptance of Soft-limiting Amplifiers

It can be seen that the triode amplifier circuits in Figures 5 and 6 have distortion characteristics which are difficult to analyze exactly. Much of the earlier work done toward analyzing vacuum tube distortion has relied on single-tone sine-wave harmonic-distortion measurements [3]. These studies have led to the proliferation of the idea that the duty-cycle shift is the main difference between solid-state and vacuum-tube amplifiers. This duty-cycle shift has some importance for the pleasantness of the sound of tube amplifiers, since even harmonics blend more musically with the fundamental. The intermodulation distortion differences between tube and transistor amplifiers are also important for explaining why electric guitarists prefer tube amplifiers.

A major factor which causes the acceptance of tube amplifiers is the ability of the amplifier to pass the riding waveform through during more portions of the overloaded modulating signal. Since this kind of transient intermodulation distortion is hard to characterize by measurements, the next section of this paper analyzes the output vs input voltage relationships of vacuum-tube amplifiers. This will serve to give insight into the nature of the grid-limit nonlinearity.

4.0 GRID LIMITING CHARACTERISTICS

In this section we examine the characteristics of the grid-limiting nonlinearity in an AC-coupled class A triode stage input circuit. It is fairly easy to detect the presence of a forward biased grid current using a dual-trace oscilloscope, as can be seen in the first half period of the triangle wave responses in Figure 9. The grid voltage Vg tracks the input voltage Vi closely, until the grid voltage increases to a sufficiently high level to forward bias the grid, causing a current flow which results in a voltage drop across the grid source resistance Rg. This grid-limiting effect is responsible for the soft-limiting properties of tube amplifiers.

The following subsections report findings from experimental and analytical work done to characterize the grid-limiting nonlinearity in a triode circuit. Pentode circuits exhibit grid limiting as well, but we restrict our attention to the discussion of triodes.

4.1 Grid Current Characteristic

A comprehensive treatment of vacuum tubes is found in the 1948 book by Spangenberg [4]. Other useful books are the physical electronics text by Seymour [5] and the RCA Tube Manual [6]. The Spangenberg and Seymour books are texts, and have an analytical emphasis. The RCA Manual provides practical usage information and characteristics for a wide range of triodes and pentodes.

The RCA manual has a section about grid current in a forward biased triode. The grid current starts to flow in a positive direction when the grid to cathode voltage Vgk increases beyond an offset voltage –Voff. This grid to cathode offset voltage is due to a complex process involving the work functions and temperatures of the grid and cathode materials, as well as the voltage between the plate and cathode Vpk. The grid current physics at the small Vgk values are very difficult to analyze. An empirical approach for characterizing the grid current seemed prudent.

The points in Figure 10 were obtained by taking DC measurements on a class A triode stage, as shown in Figure 5. It shows the grid current Ig on the vertical axis, and the grid to cathode voltage Vgk on the horizontal axis. The plate voltage Vp is not shown, but measurements show that it varies with different values of Vgk. This plate voltage variation becomes less as grid limiting occurs. The effects of the plate voltage variation are intrinsically imbedded in the points shown in Figure 10.

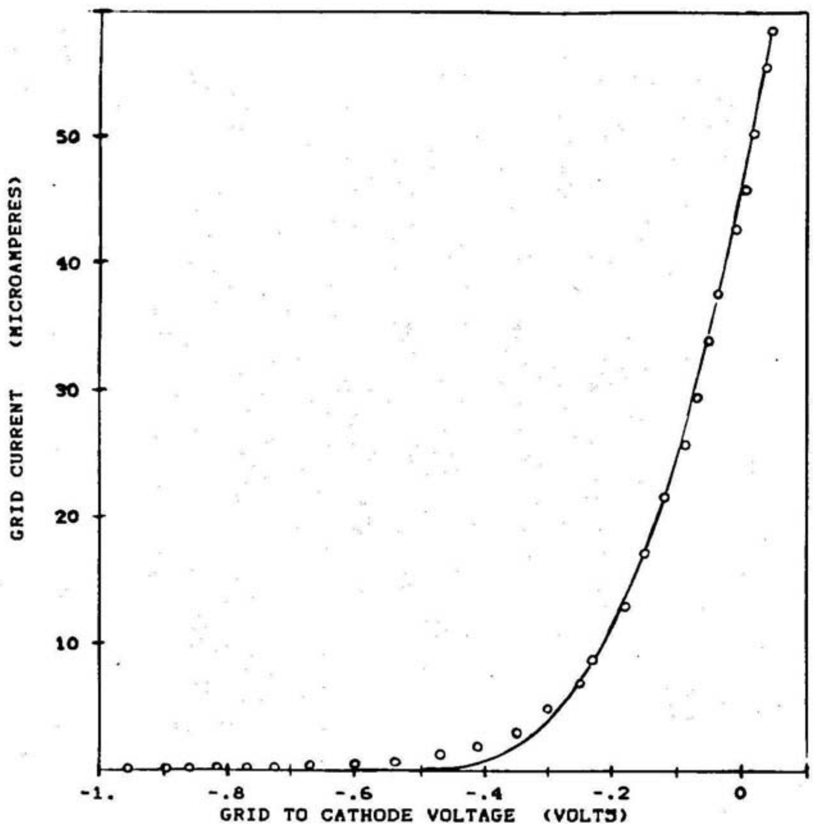

Figure 10 - Grid current vs. grid to cathode voltage, 12AX7 triode. Circles indicate measured points, curve shows fitted equation. Ig = 3.le-4 * (Vgk + .53)**3 amperes.

Inspection of Figure 10 reveals two distinct regions in the grid current characteristic. At voltages slightly higher than the negative offset voltage -Voff the characteristic has an exponential quality to it. Attempts at fitting exponential functions to the data points were favorable for the points near the offset voltage, but wouldn't work for the points with Vgk closer to 0. Attempts at fitting the points to a power function worked well for all of the points except those near the offset voltage. The fitted power function is shown as the solid curve in Figure 10.

The portion of the curve away from the offset region is approximated by the fitted power function:

Ig = a • (Vgk + Vo)**b (1)

with a = 3.le-4 amperes, Vo = .53 volts, and b = 3.0 .

For Vgk values much greater than the offset voltage -Voff, the analytical treatment in Spangenberg [4] provides insight. In this region the analysis is simplified by ignoring temperature and material work-function effects. The following three equations are obtained from Spangenberg [4]. He makes no mention of the offset voltage, and it was assumeed to be 0 in all derivations in his book.

The crossection of the positive grid which intersects the electrons accelerating towards the more positive plate, diverts the flow of some of the incident electrons passing the grid surface. In this region the grid current and the plate current follow the current division relationships, which are found in Spangenberg [4]:

Ip = Is /{1 + 1/[d *(Vpk/Vgk)**.5]} (2)

and

Ig = Is /[1 + d *(Vpk/Vgk)**.5] (3)

where

Is = G*(Vgk + Vpk / MU)**1.5 (4)

is the total space current (ignoring secondary emission). The triode parameters gain factor MU and purveyance G, are not exactly constants, since they vary with operating region.

Since the relationships in Eqs. (2 - 4) are all power functions (considering one of the two voltages to be constant), it is not surprising that the points away from the offset region follow an approximate power function relationship. The important point is that for a wide portion of the operational grid-limiting range of the input circuit, the grid current can be approximated by a power function of the grid to cathode voltage.

4.2 Power Function Approximation for Grid Circuit

It is easier to write the input voltage which would result from a given grid voltage, rather than find the grid voltage in terms of the input. We can write the following relationship (see Figure 5):

Vik Vgk + Rg *Ig(Vgk) (5)

where the parenthesis after Ig denote functional dependance.

Substituting Eq. (1) into Eq. (5), results in the following:

Vio = Vgo *[1 + a * Rg*(Vgo)**(b-1)] (6)

where

Vio = Vik + Vo (7)

and

Vgo = Vgk + Vo (8)

This relationship is plotted for several values of Rg in Figure 11, using a = 3.1e-4 amperes and b = 3.0 . Note the smoothness of the limiting affect implied by this power relationship. The actual points measured for Rg = 470 K-ohm are also shown in Figure 11. Note that for all points except those near the offset region the power approximation holds fairly well.

The power function relationship in Eq (6) has an interesting scaling property. Changing variables in Eq (6) using:

Vgs = Vgo/s . Vis = Vio/s (9)

yields

Vis = Vgs*[l + a * s**(b-1) * Vgs**(b-1)] (10)

Scaling the voltages results in the same functional form, but with a different grid-limit factor. As can be seen by looking at Figure 11, the result of magnifying the lower range of a curve with a large limit factor is another curve with a smaller limit factor.

By differentiating Equation (6) with respect to Vgo, we arrive at the following approximation for the incremental loss of the input stage:

dVio/dVgo = 1 + b * Rg * Vgo**(b-1) (11)

We use the concept of incremental loss because it has a simpler functional form than its inverse, the incremental gain. The incremental loss is plotted in dB versus the compression level, also in dB, in Figure 12, along with a line to indicate linear operation for reference. Note that the incremental loss is not severe even for large amounts of compression. As stated elsewhere in this paper, the nonzero incremental gain in overload is the major factor contributing to the success of vacuum tube amplifiers in electric guitar applications.

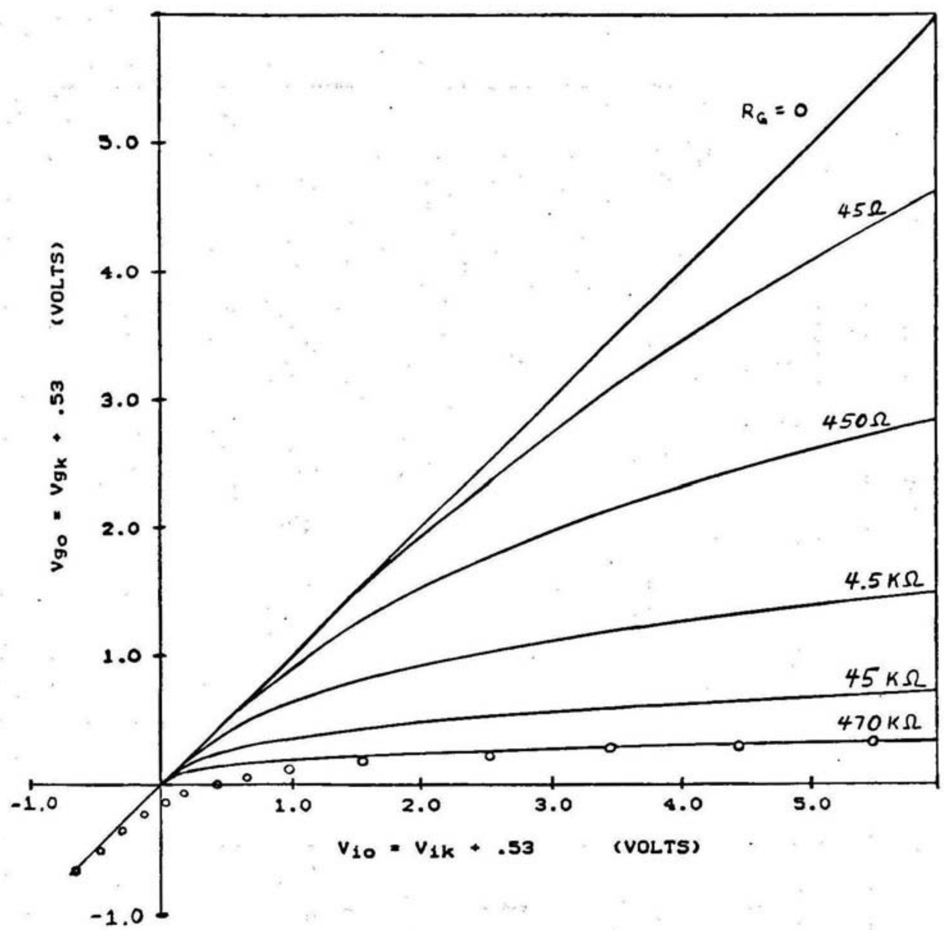

Figure 11 - Power function grid limit curves, for various values of grid resistance, along with actual measured points for Rg = 470 K-ohm. Curves plotted using inverse function Vio = Vgo * [l + 3.14e-4 * Rg * (Vgo)**2] .

5.0 CONCLUSIONS

The following points have been presented in this paper:

Soft limiting is a desirable effect for electric guitar amplifiers to have. Since the guitar has multiple waveforms mixed into its signal, a soft limiting amplifier lets more of the weak signals through the amplifier at high signal levels.

Most solid-state amplifiers have symmetric "brick wall" hard limits on both sides of the output waveform. The symmetry causes a predominance of odd-harmonic distortion components, while the hard limiting produces undesirable intermodulation distortion effects.

The voltage drop across the grid circuit source resistance, caused by grid current flow, is know as grid limiting and is responsible for the soft limiting effects of tube amplifiers.

Emulation of the grid limit effect using solid-state diode circuits will not produce the same results as a vacuum tube. Tube grid currents follow a power function relationship with voltage and solid-state devices follow an exponential relationship. The exponential relationship causes a faster transition into a hard limit region of operation than the power function relationship found in tube circuits.

REFERENCES

1) Cabot, Richard C.; "Perception of Nonlinear Distortion" ; presented at 2nd AES International Conference, May 11 - 14, 1984; Conference paper C1004.

2) Bussey, W. Stephen and Haigler, Robert M ; "Tubes Versus Transistors in Electric Guitar Amplifiers" ; IEEE Conference Paper CH1610-5/81/0000-0800, 1981.

3) Hamm, Russel O. ; "Tubes vs Transistors - Is there an Audible Difference?" ; Journal AES, May 1973, Vol 21 no. 4 .

4) Spangenberg, K.; "Vacuum Tubes" ; McGraw Hill 1948.

5) Seymour J. ; "Physical Electronics"; Halstead Press 1972

6) "RCA Receiving Tube Manual"; RC-30; RCA Corporation 1975.

7) Hsu H. P. ; "Fourier Analysis" ; Simon and Schuster 1970

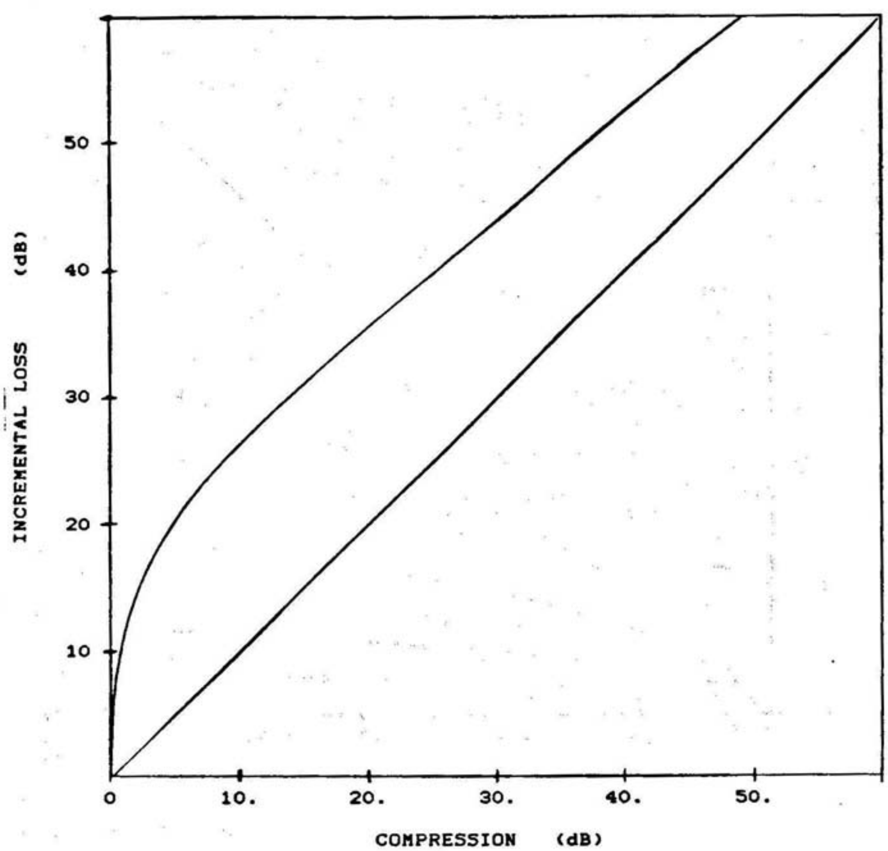

Figure 12 - Incremental loss in dB versus compression in dB for power function grid limit curves in Fig. 11. Note that for wide region incremental loss is greater than compression factor by 10 dB.