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Over-Threshold Power Function Feedback Distortion Synthesis

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ABSTRACT

This paper describes an approach to nonlinear distortion synthesis, which uses Over-Threshold Power Function (OTPF) Feedback. The linear gain of an OTPF Feedback distortion synthesizer (using a high gain amplifier) is determined by a linear feedback element. When the output signal becomes greater than a positive threshold value, or less than a negative threshold value, additional OTPF feedback is applied to the distortion synthesizer. The action of this OTPF Feedback Distortion synthesis closely emulates the soft limiting input/output response characteristics of Vacuum tube triode grid limit distortion. An important feature of an OTPF feedback distortion synthesizer that it always behaves as an instantaneous soft limiter, and never results in clipping of the output signal peak levels (even at maximum allowable peak input signal levels), if its non-linear gain constants are set optimally. The paper also describes both circuit and software plug-in realizations of distortion synthesizers which employ Over-Threshold Cubic Function Feedback.

1. INTRODUCTION

This paper describes an approach to nonlinear distortion synthesis, which is the subject of an abandoned patent [1]. Over-Threshold Power Function (OTPF) feedback closely emulates the soft limiting input/output response characteristics of Vacuum tube triode grid limit distortion, as described in [2], [3]. A summary of the findings in [2] are included in an Appendix to this paper. As the grid to cathode voltage (Vgk) of a class A common cathode triode amplifier becomes greater than a threshold (-.9V for a 12AX7), grid current flows and causes a voltage drop across the source resistance. This voltage drop acts as non-linear negative feedback acting on the grid to cathode voltage (Figure A-4). Figure A-3 shows that for values of Vgk greater than a threshold (-.53 V), this grid current flow can be modeled as a cubic power function of the portion of Vgk over that threshold.

OTPF Feedback synthesis provides soft limiting to both the positive and negative portions of the signal, and does not try to emulate other triode effects, such as plate cutoff [3] or asymmetric duty cycle shift [4].

2. OVER-THRESHOLD POWER FUNCTION FEEDBACK FUNCTION

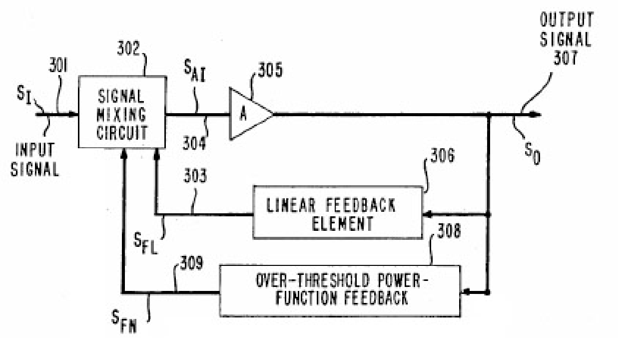


Figure 1 – OTPF Feedback Distortion Synthesizer

Figure 1 is a conceptual diagram of an OTPF feedback Distortion Synthesizer, the operation of which is defined by Equations (1) thru (4), where: Si is input signal (301); So is output signal (307); Sfn is non-linear feedback (309); Gain is determined by linear feedback element (306); Stp and Ktp are threshold and non-linear feedback attenuation constant for the positive portion of the output signal; Stn and Ktn are threshold and non-linear feedback attenuation constant for the negative portion of the output signal; and b is the power constant.

(1) $$\mathrm{Si} = \mathrm{So}/\mathrm{Gain} + \mathrm{Sfn}$$

(2) $$\mathrm{Sfn} = \mathrm{Ktp} * (\mathrm{So} - \mathrm{Stp})^{b}, \quad \mathrm{So} \geq \mathrm{Stp} \geq 0$$

(3) $$\mathrm{Sfn} = 0, \quad \mathrm{Stn} \leq \mathrm{So} \leq \mathrm{Stp}$$

(4) $$\mathrm{Sfn} = -\mathrm{Ktn} * \left|(\mathrm{So} - \mathrm{Stn})\right|^{b}, \mathrm{So} \leq \mathrm{Stn} \leq 0$$

Assuming the open-loop gain of amplifier A (305) is large, the linear gain, Gain, of the synthesizer is determined by the transfer characteristic of the linear feedback element (306). When the output signal, So, becomes greater than a positive threshold value, Stp, or less than a negative threshold value, Stn, OTPF feedback, Sfn, (from 308) is applied to the signal mixing circuit (302).

Anti-causal analysis simplifies the understanding the operation of an OTPF feedback distortion synthesizer. Figure 2 shows a normalized graph of the input signal level, Sin, which would be required to cause the production of a given output signal level, Sout, with linear region gain of 5, and a cubic power function.

For the region above the positive threshold, Stp = .5, the effect of cubic power function feedback is shown for four different feedback gain constants: Ktp = 0 , .5 * KtpOpt. ; KtpOpt, and 2 * KtpOpt. For the region below the negative threshold, Stn = -.7, the effect of cubic power function feedback is shown for four different feedback gain constants: Ktn = 0 , .5 * KtnOpt, KtnOpt, and 2 * KtnOpt .

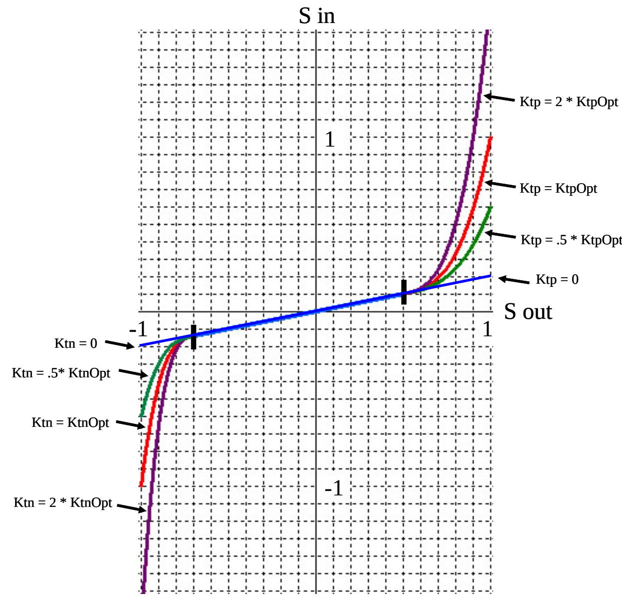


Figure 2 – Anti-causal Graph of OTPF Feedback - Gain= 5, Stp = .5, Stn = -.7, b = 3

The optimum values for feedback gain, KtpOpt and KtnOpt are defined as the specific values which result in the maximum allowable peak input signal level being equal to the maximum allowable peak output signal level, for the positive and negative portions of the output signal, respectively. An important feature of an OTPF feedback distortion synthesizer that it always behaves as an instantaneous soft limiter, and never results in clipping of the output signal peak levels (even at maximum allowable peak input signal levels), if the non-linear gain constants not set to be less than these optimum values.

By substituting the values Si = Smp and So = Smp in Equations (1) and (2), where Smp is the maximum allowable positive output signal level, and solving for the value of Ktp = KtpOpt which would allow these values, we arrive at:

(5) $$\mathrm{KtpOpt} = \mathrm{Smp} * \frac{(\mathrm{Gain} - 1) * \mathrm{Gain}}{(\mathrm{Smp} - \mathrm{Stp})^{b}}$$

Similarly, by substituting Si = Smn and So = Smn, in Equations (1) and (4), where Smn is the minimum allowable negative output, we arrive at:

$$\text{(6)} \quad \mathrm{KtnOpt} = -\mathrm{Smn} * \frac{(\mathrm{Gain}-1) * \mathrm{Gain}}{\left|(\mathrm{Smn}-\mathrm{Stn})\right|^{b}}$$

3. CIRCUIT REALIZATION USING OVER-THRESHOLD CUBIC FEEDBACK

A circuit diagram of an OTPF Feedback Distortion Synthesizer using an adjustable over-threshold cubed current-feedback path, is shown in Figure 3. Dotted line boxes are used to surround circuit elements in Figure 3, corresponding to blocks in Figure 1 as follows: box 602 corresponds to block 302;. boxes 604 and 605 together correspond to block 308; box 603 corresponds to block 306; and a Texas Instruments TL072 high-gain operational amplifier 601 is used as amplifier 305.

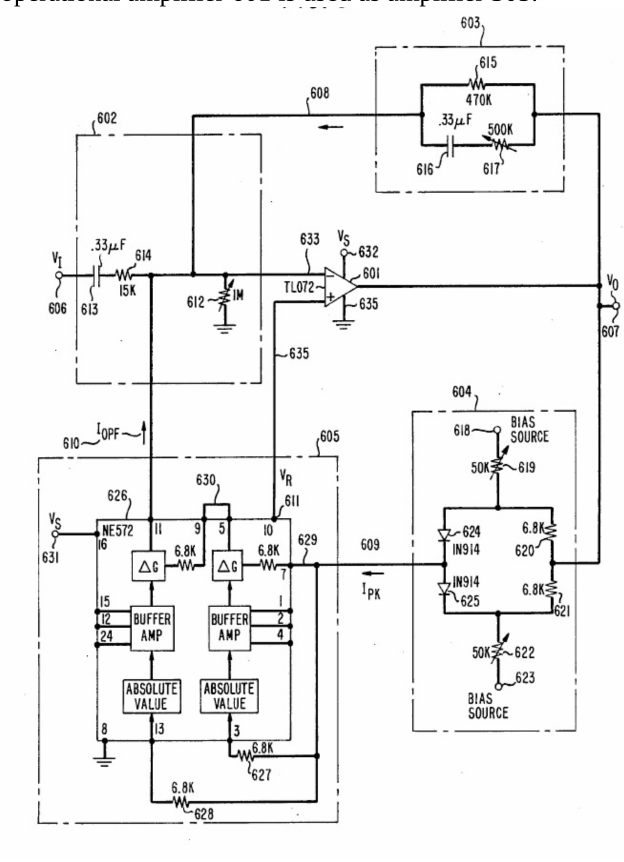


Figure 3 – Over-Threshold Cubic Feedback Distortion Synthesizer, comprising:Amplifier (601); Signal mixing circuit (602); Linear Feedback (603); Peak pass circuit (604); and Over-Threshold Cubic Feedback (605)

Amplifier 601 has differential input terminals 633 and 634 driven by signal-mixing circuit 602. The output DC bias voltage level of amplifier 601 is set using nominal 2.5 Volt reference voltage 611 (provided by Signetics NE572 integrated circuit 626), adjustable resistor 612 and DC feedback resistor 615. A supply (9 to 15V), shown as Vs, is connected to terminals 631 and 632. Output voltage 607 drives linear feedback element 603 and peak-pass circuit 604.

Resistors 627, 628 and NE572 internal resistor connected to input terminal 629, together serve in parallel as load, Ri = 6.8K/3, for peak-pass circuit 604 (a virtual reference, Vr = 2.5V, is maintained within NE572). Bias voltage sources are connected to terminals 618 and 623 to set threshold. When output voltage 607 is greater than a positive threshold Vtp (predetermined by setting bias voltage source 618, Vbp, and resistors 619, Rbp, and 620, Rs), the diode 624 conducts. When the diode 624 conducts, peak-over-threshold current 609 is positive and its magnitude is equal to the difference between the output voltage 607 and the positive threshold voltage Vtp, multiplied by a transconductance set by resistors 619 and 620.

$$\text{(7)} \quad \mathrm{Vtp} = \mathrm{Vr}\,\frac{\mathrm{Rbp}+\mathrm{Rs}}{\mathrm{Rbp}} - \mathrm{Vbp}\,\frac{\mathrm{Rs}}{\mathrm{Rbp}}$$

$$\text{(8)} \quad \mathrm{Ipk} = \frac{1}{\mathrm{Rs}+\mathrm{Ri}+\mathrm{RsRi/Rbp}}\left(\mathrm{Vo}-\mathrm{Vtp}\right),\ \mathrm{Vo} \geq \mathrm{Vtp}$$

When the output voltage 607 is less than the negative threshold Vtn (predetermined by setting bias source 623, Vbn, and resistors 621, Rs, and 622, Rbn), diode 625 conducts. When diode 625 conducts, peak-over-threshold current 609 is negative and its magnitude is equal to the difference between the output voltage Vo and negative threshold voltage Vtn, multiplied by a transconductance set by resistors 622 and 621.

$$\text{(9)} \quad \mathrm{Vtn} = \mathrm{Vr}\,\frac{\mathrm{Rbn}+\mathrm{Rs}}{\mathrm{Rbn}} - \mathrm{Vbn}\,\frac{\mathrm{Rs}}{\mathrm{Rbn}}$$

$$\text{(10)} \quad \mathrm{Ipk} = \frac{1}{\mathrm{Rs}+\mathrm{Ri}+\mathrm{RsRi/Rbn}}\left(\mathrm{Vo}-\mathrm{Vtn}\right),\ \mathrm{Vo} \leq \mathrm{Vtn}$$

A polarity-preserving cubing circuit 605 is realized using a Signetics NE572 integrated circuit 625, connected as shown. NE572 buffer amp terminals, which can be used to connect components for setting attack and release times, are left unconnected.. This allows integrated circuit 626 to provide a pair of four-quadrant analog current multipliers, with each multiplier having one input driven by an internal absolute value circuit. Peak-over-threshold current 609 is divided evenly into three separate NE572 input currents by resistors 628, 627 and an internal resistor connected to input terminal 629. The current through jumper wire 630 is proportional to a polarity-preserved square of peak-over-threshold current 609. To realize over-threshold cubed current feedback, jumper wire 630 is used to drive one input of the second current multiplier stage. The other input of the second current multiplier stage is connected to accept the current through resistor 628.

Output 610 is over-threshold cubed feedback current, having the same polarity as peak-over-threshold current 609, and having magnitude proportional to the peak-over-threshold current level raised to the third power The circuits in boxes 604 and 605 realize the OTPF equations (2) and (4), where So is a voltage signal, Spk and Sfn are current signals, and constant b is equal to 3.

The linear AC gain of the system in Figure 3 is set by adjusting AC feedback resistor 617 in series with capacitor 616. Signal-mixing circuit 602 mixes negative feedback currents 608 and 610 with input current through resistor 614 in series with capacitor 613, to drive the amplifier negative input terminal 633.

There is an inherent difficulty associated with adjusting the controls for the OTPF feedback for the circuit in Figure 3. Rbn and Rbp values affect both the thresholds and transconductance constants in Equations (7) thru (10). It is this difficulty that led to development of a software plug-in version of the OPTF Feedback distortion synthesizer. In cases where a hardware realization of OTPF Feedback synthesizer is desired, the software plug-in can be utilized, as a design tool, to determine appropriate values for the thresholds (Stp, Stn) and non-linear gain constants (Ktp, Ktn). Once determined, these threshold and gain constants can then be used to design a hardware realization by selecting appropriate fixed values for the peak pass circuit elements, using Equations (7) thru (10).

4. SOFTWARE FILTER PLUG-IN REALIZATION OF OVER-THRESHOLD CUBIC FEEDBACK SYNTHESIZER

The Tuboid software plug-in, available for download at www.tuboid.com, is a DirectX audio filter implementation of an Over-Threshold Power Function (OTPF) feedback distortion synthesizer. The name “Tuboid” was chosen to connote an intelligent device which emulates the distortion characteristics of a vacuum tube.

The approach taken in the design of this software plug-in is to employ a mapping array, which stores 16 bit twos complement integer signal value (representing the output) in each element of the array, where the index for the array corresponds to a scaled integer value of the input signal value. Conceptually, with an input scaling factor of 1, the mapping array would require an array of 16 bit integers, with dimension of 65536. The actual implementation of the Tuboid plug-in uses a input scaling factor of 256, which requires an array dimension of only 256 (with linear interpolation used to compute the output signal value for inputs which are between the scaled input values).

The mapping array is populated by iterating over the set of possible output values, applying the OTPF equations to compute the required input value for each output, and when a change of the input index (corresponding to the scaled input value) is detected, the output value is entered in the array for that index. In effect the algorithm produces the inverse of the anti-causal OTPF feedback function for a given set of gain constants.

The software plug-in controls are shown in the top portion of Figure 4. They are:

- the linear gain (labeled “Gain”) of the synthesizer
- the normalized threshold level for the positive output signal (labeled “Threshold Pos”),
- the normalized threshold level magnitude for the negative output signal (labeled “Threshold Neg”),
- the multiplier to apply to the optimal non-linear gain constant (i.e., KtpOpt) for the positive side of the output signal (labeled “Squash Pos”, values >= unity), and,
- the multiplier to apply to the optimal non-linear gain constant (i.e., KtnOpt) for the negative side of the output signal (labeled “Squash Neg”, values >= unity).
- the non-linear transfer characteristic is shown as a graph (instantaneous output signal level on vertical

axis, versus instantaneous input signal level on horizontal axis). This graph is generated by setting one pixel for each of the mapping array index values. The graph area of the window is cleared and 256 new pixels are drawn whenever a control value is changed by the user.

The control parameters are set up to disallow ktp and ktn values which will result in clipping of the output signal. That is why the “squash” values are only allowed to be set to greater than or equal to 1. A squash value of 1 sets the synthesizer to operate with nonlinear gain constant set to the optimal values (KtpOpt and KtnOpt) as shown in Figure 2. This feature guarantees that the Tuboid filter plug-in never clips the output signal under all possible input signal conditions.

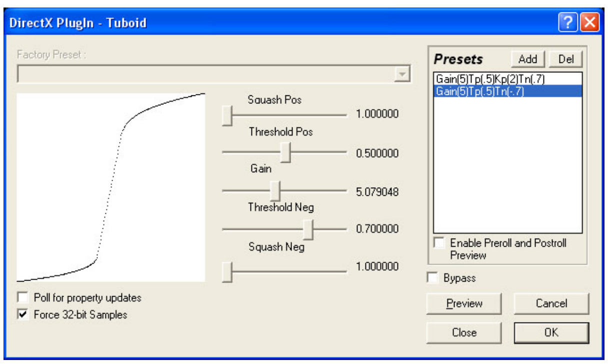
Whenever the plug-in user changes one of the control parameter values, the mapping array is recalculated, and the resulting input/output characteristic curve is drawn in the control panel for the plug-in. The plug-in is a software filter which uses the mapping array to calculate the output signal value for each sampled input signal value.

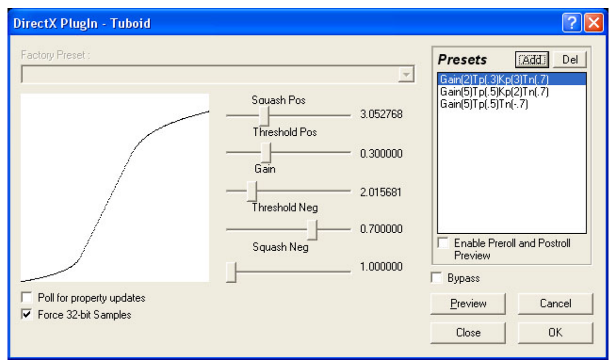
Figure 4 – Adobe Audition Screen Clips – Tuboid Plug-in settings and Full Scale Triangle Wave Response: Gain = 5, Tpos = .5, TNeg = .7

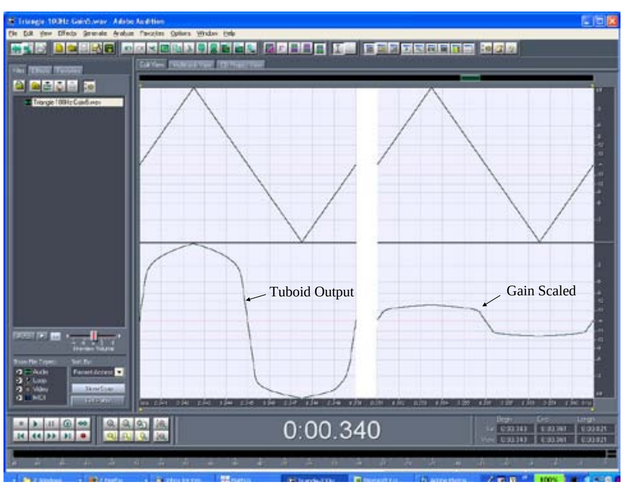
Figures 4 and 5 are screen clips showing the results of applying two different setting of the software plug-in to a full scale 100 Hz triangle wave.

Figure 4 shows an example of the software plug-in, set to operate as shown in Figure 2, using the optimal values KtpOpt and KtnOpt (i.e, unity Squash values). The upper waveform is the 100 Hz input triangle wave. The lower left waveform is the output of applying the software plug-in as an effect. The lower right waveform is the software plug-in output, scaled down to the relative level of the input (i.e., the output signal level divided by the linear gain), demonstrating its soft limiting of the input signal.

Figure 5 shows a the results of a different setting of the software plug-in, with Gain =2, and a positive Squash value of 3. Note that, because the linear gain is smaller than that in Figure 3, the resulting instantaneous distortion of the output signal is less.







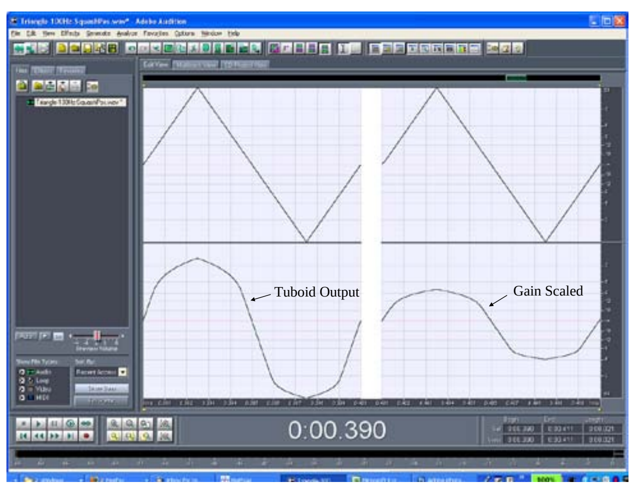


Figure 5 – Adobe Audition Screen Clip – Tuboid Plug-in settings and Full Scale Triangle Wave Response: Gain = 2, Tpos = .3, TNeg = .7, SquashPos = 3.

5. DEMONSTRATION AUDIO CLIPS

Fig 6 shows a relatively low gain, Asymmetric, distortion synthesizer setting which is typical of the kind of low level distortion associated with vacuum tube preamps used in high fidelity situations (e.g., microphone pre-amps, vacuum tube equalizers).

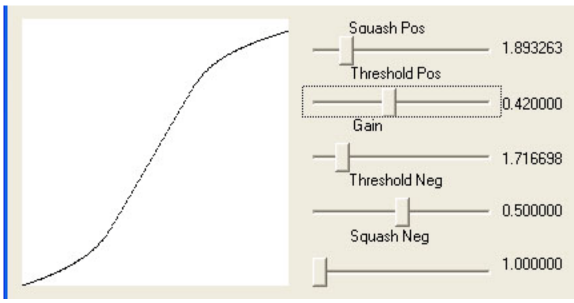


Figure 6 OTPF Feedback settings: gain = 1.72 (4.7 dB), Tpos = .42, SqPos=1.9, Tneg=.5

Figure 7 shows the effect, using the settings in Figure 6, of the ODPF Feedback distortion synthesizer on a 3 second clip of a loud vocal phrase along with a lower level orchestra background (it is the "oh yeah" refrain from Ray Charles "I've Got a Woman").

Figure 8 shows an audio file (available at http://www.coastenterprises.com/OTPF/demoClips) with two clips separated by .5 sec silence: the input waveform; followed by the output of the synthesizer scaled down by 4.7 dB.

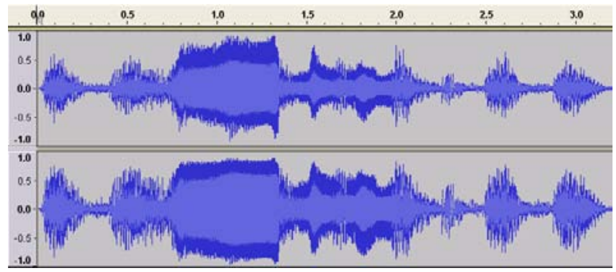


Figure 7 Top: input waveform of vocal with orchestra Bottom: Synthesizer plug- in output

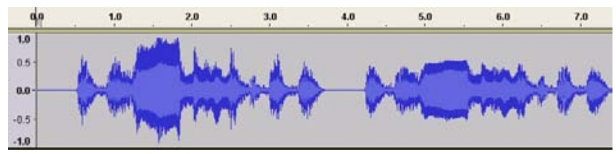


Figure 8: Demo sound clips: Input, Output scaled down by 4.7 dB

Figure 9 shows a two superimposed scope traces, of a 100 ms section of the clip, starting at .72 seconds. The larger one is the input, and the smaller one is the soft limited output of the synthesizer scaled down by 4.7 dB.. Note that the small "undulations" on the peaks are followed by the soft limited output.

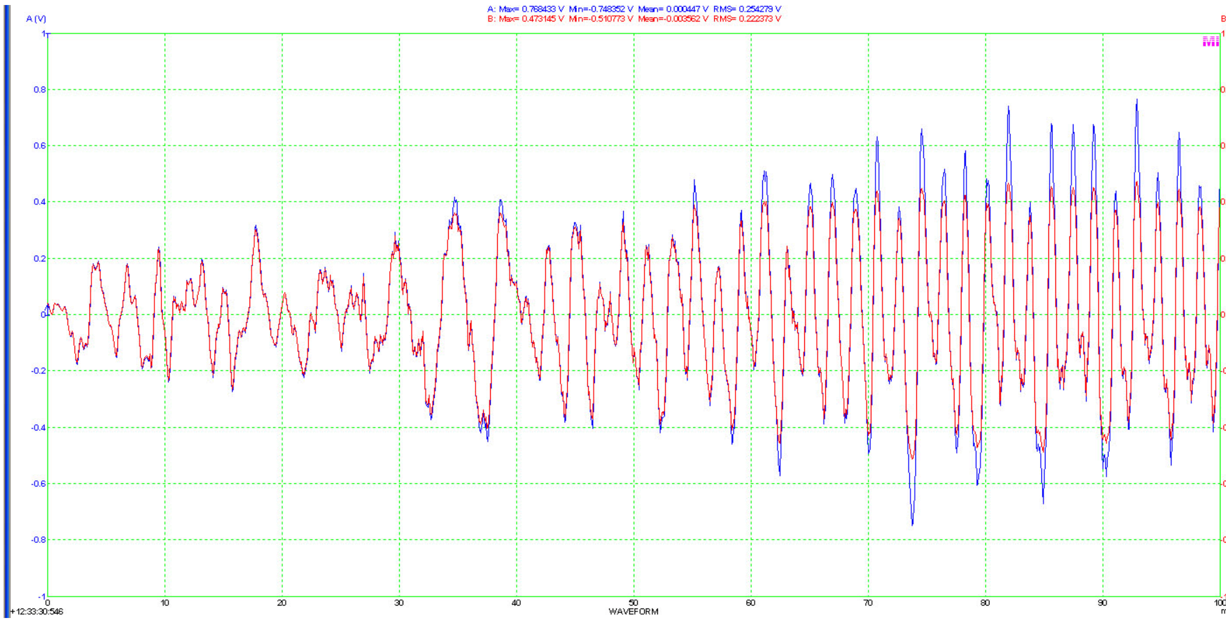


Figure 9 – 100 ms dual-trace scope clip starting at .72 seconds. input, and soft limited output scaled down by 4.7 dB

Fig 10 shows a fairly symmetric, distortion synthesizer setting which is typical of the kind of distortion levels associated with vacuum tube preamps used in guitar amplifiers.

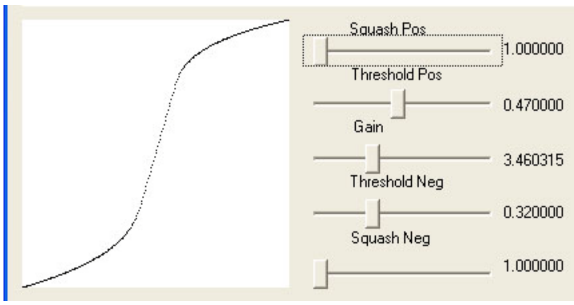


Figure 10 - OTPF Feedback settings
:gain = 3.46 (10.8 dB), Tpos = .47, Tneg=.32

Figure 11 shows the effect, using the settings in Figure 10, of the ODPF Feedback distortion synthesizer on a 4 second clip of a Fender Stratocaster electric guitar lick. The gain of the synthesizer was carefully set while listening to the output, to attain the desired level of distortion.

Figure 12 shows an audio file (available at http://www.coastenterprises.com/OTPF/demoClips) with three clips separated by .5 sec silence: the input waveform; followed by the output of the synthesizer scaled down by 10.8 dB, followed by the non-normalized synthesizer output.

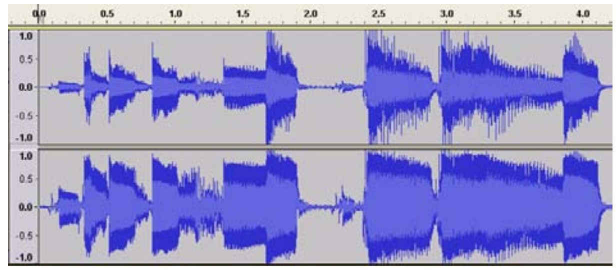


Figure 11: Top: input waveform of guitar lick
Bottom: Synthesizer plug- in output

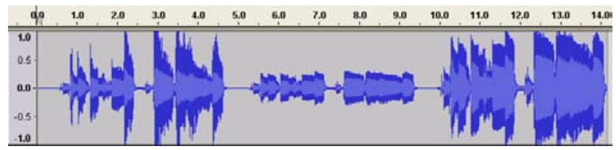


Figure 12 - Demo clips: Input, Output scaled down 10.8 dB, un-scaled Output

Figure 13 shows a two superimposed scope traces, of a 50 ms section of the clip, starting at 3 seconds; the larger one is the input, and the smaller one is the soft limited output of the synthesizer scaled down by 10.8 dB. Note again, that the small "undulations" on the peaks are followed by the soft limited output.

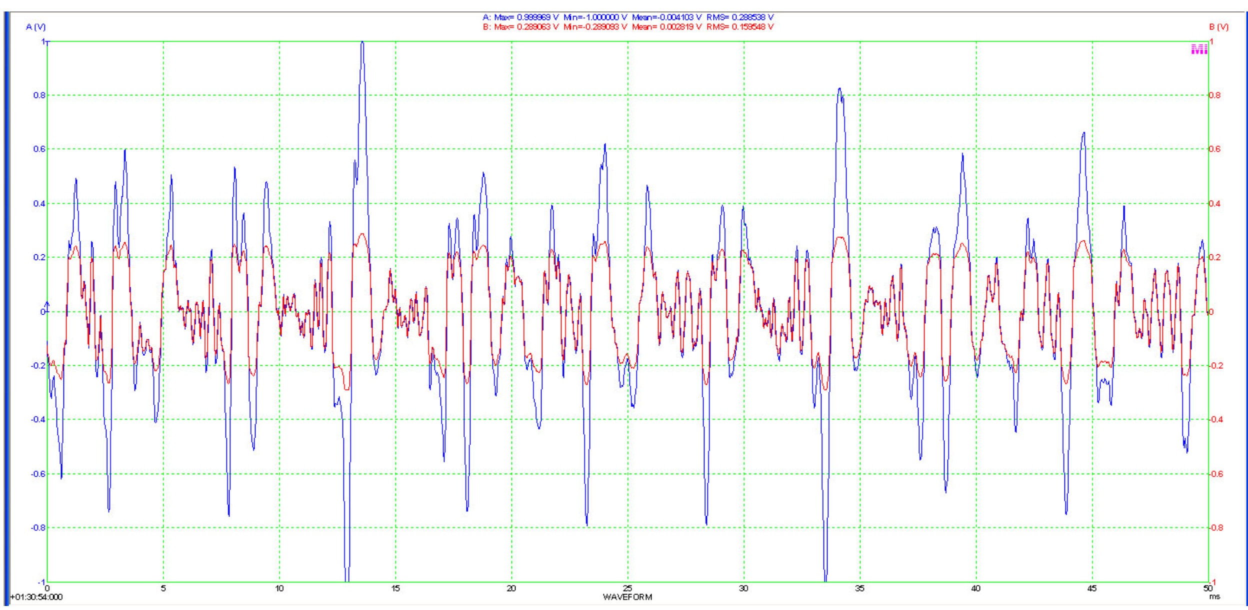


Figure 13 - 50 ms dual-trace Scope clip starting at 3 sec: input, and soft limited output scaled down by 10.8 dB.

6. CONCLUSIONS

This paper has presented an approach (with both hardware and software plug-in realizations) to synthesis of a soft-limiting form of non-linear distortion, which closely mimics the effects of vacuum tube grid limit distortion. A type of non-linear feedback (OTPF), is applied separately to the positive and negative portions of an input signal. As such, it does not directly emulate any single vacuum tube amplifier configuration, but, instead, produces a flexible effect which can be controlled using a well defined set of control parameters. It is shown, that with optimal parameter settings, the distortion synthesizer will not allow hard clipping.

In actual guitar amplifier applications using vacuum tube triode stages (see [3], [4]), the sound from the tube distortion is further tailored by adjusting equalization both before and after the distortion stage. Also, the output tube stages and the output transformer have significant affect on the overall sound. At the levels of distortion in actual guitar amps, the high-pass filtering due to the loudspeaker removes some of the harshness introduced by the distortion. None of these effects are demonstrated in this paper; however they can be applied in addition to the effect of this non-linear distortion synthesizer.

The setting of input level and gain of the synthesizer have a large impact on the overall "tone" and effect of the distortion. With proper setup and level matching, the output signal may have its signal peaks instantaneously reduced, while allowing the higher frequency "undulating" portions of the signal around these peaks to pass thru to the output (i.e., it does not clip). This can be seen in the dual-trace scope clips shown in Figures 9 and 13.

In closing, I admit that designing distortion is a difficult subject, and, from experience using OTPF feedback, it is easy to configure distortion which sounds horrible for a given type of input. The software plug-in can be used to determine an effective set of design parameters, which can then be used to produce a hardware design suitable for any particular soft-limiting application.

7. ACKNOWLEDGEMENTS

This work has been supported by considerable use and evaluation (by too many guitar players to list) of both the hardware and software realizations of OFPF Feedback distortion synthesizers.

8. REFERENCES

[1] "Nonlinear distortion synthesizer using over-threshold power-function feedback" US Patent 4,710,727 (December 1, 1987, Inventor Thomas E. Rutt), now abandoned

[2] "Vacuum Tube Triode Nonlinearity as Part of The Electric Guitar Sound", Thomas. E. Rutt, Presented at the 76th Convention of Audio Engineering Society 0ctober 8-11, 1984, New York (Paper number 2141).

[3] "Designing Valve Preamps for Guitar and Bass", Merlin Blencowe, ISBN: 978-0-9561545-0-7

[4] "A Musical Distortion Primer", R.G. Keen, http://www.geofex.com/effxfaq/distn101.htm

APPENDIX A – AES PAPER ON GRID LIMIT DISTORTION

Figures A-1 thru A-4 are reproduced from [2], and provide a summary of the findings of that paper.

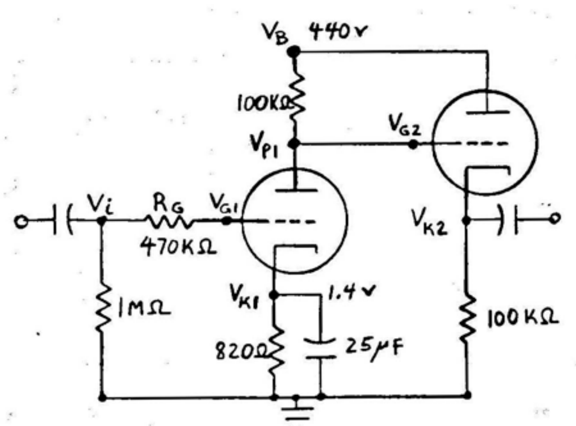


Figure A-1 - Class A triode stage with DC coupled cathode follower stage.

Figure A-1 shows a typical guitar preamp circuit, comprising a class A common Cathode stage directly coupled to a Cathode follower stage. Connecting the cathode follower applies a soft limiting effect to the positive portion of the plate voltage, as shown in Figure A-2.

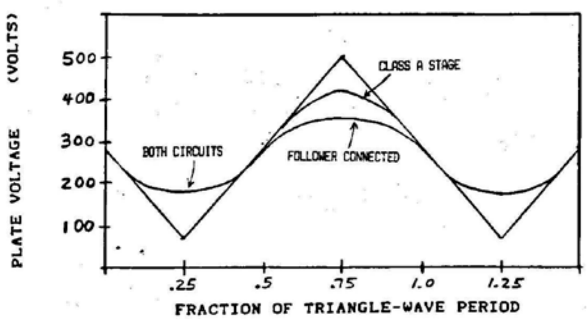


Figure A-2: Triangle-wave response, with moderate overload.

Figure A-2 shows the Plate voltage of class A triode stage of Figure A-1, shown along with scaled and shifted input triangle wave. In first half cycle, the first stage grid current feedback distortion is evident. In second half cycle the plate voltage Vpl with follower connected (bottom curve) is decreased relative to the pure class A stage without the follower connected (upper curve), due to negative feedback thru the plate resistor resulting from grid current flowing into cathode follower).

Note that with the follower connected, the circuit exhibits soft-limiting effects for both the positive and negative portions of output signal.

Figure A-3 plots measured points showing Grid Current grid to cathode voltage (Vgk) for the circuit in Figure A-1, using a 12AX7A dual triode. The solid curve is a fitted power function which is fairly accurate for Vgk values above -.53 volts.

Figure A-4 shows the non-linear feedback effect of grid limit current flow due to over-threshold values of Vgk. The solid curves are theoretical (using the fitted equation from Figure A-3) for different values grid resistance. The actual measured points for 470K ohm grid resister are also shown as circles.

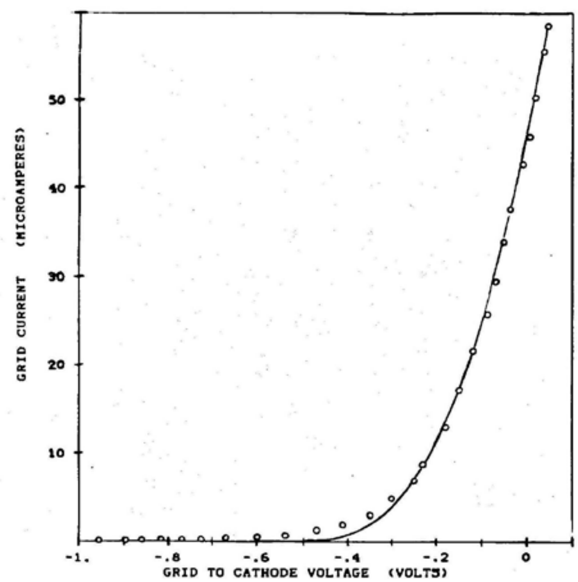


Figure A-3 - Grid current vs. grid to cathode voltage, 12AX7 triode. Circles indicate measured points, solid curve shows fitted equation.

Ig = 3.le-4 * (Vgk + .53)**3 amperes.

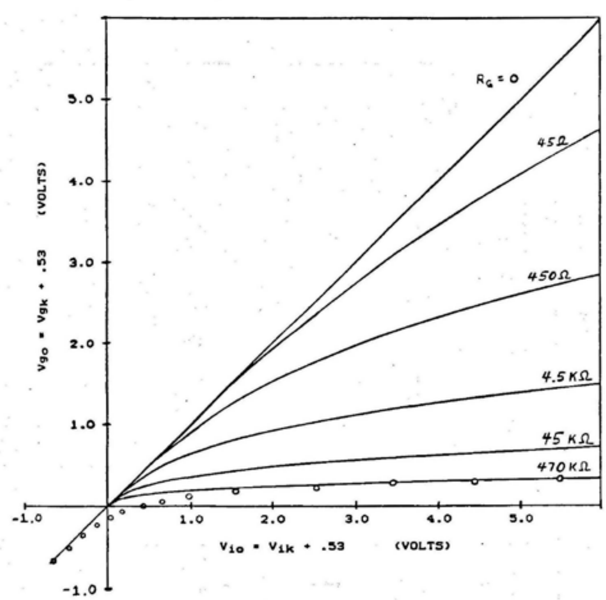


Figure A-4 – Grid Current Feedback: Vio = Vgo + a * Rg*(Vgo)**(3) , a = 3.le-4 amperes