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Non-Ideal Operational Amplifier Emulation in Digital Model of Analog Distortion Effect Pedal

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ABSTRACT

Digital models of analog guitar effects pedals have largely ignored the impact of non-ideal components on the resulting timbre, though the physical limitations of analog components are sometimes key to achieving the intended effect. The signature sound of the Pro Co RAT is largely attributed to the non-ideal characteristics of the Motorola LM308 operational amplifier, particularly the slew-rate, gain-bandwidth product and supply voltage. Analysis of harmonic and spectral content shows that the inclusion of these non-ideal component characteristics results in a more accurate recreation of the Pro Co RAT distortion effect. In a comparison of real-time digital models, the additional computational cost of the non-ideal model was negligible.

1 Introduction

Digital modelling of analog circuits has seen significant improvements in accuracy and fidelity but often at the expense of higher computational cost and mathematical complexity. As a result, many modelled components are treated as ideal in order to simplify calculations and conserve resources [1]. Generally, introducing non-ideal characteristics will increase the complexity of the model, which may require a more than marginal increase in computer processing power in exchange for a marginal change (not necessarily positive) in timbral quality. For example, in most cases it would be unnecessary to model an operational amplifier (Op-Amp) as a non-ideal component because Op-Amps are typically intended to be tonally transparent in their use cases. While introducing some of the inherent physical limitations of an Op-Amp may result in a more realistic sound, it may not actually serve the intent of the circuit, model or plugin-in. However, the designs of many guitar effects pedals incorporate the timbral qualities created by non-ideal components as part of the intended effect [2]. In the case of the Pro Co RAT distortion effect pedal, the non-ideal characteristics of the Motorola LM308 Op-Amp [3] (or a comparable Op-Amp) are integral to the signature sound of the analog effect.

Three non-ideal Op-Amp characteristics were selected based on hypothesized contribution to the timbre of the RAT distortion effect: slew rate, gain-bandwidth product and supply voltage.

2 Digital Model of the Pro Co RAT

The Pro Co RAT distortion pedal is a well-known guitar effect used on many records since its release in 1978. The circuit can be broken down into three sections: the gain and clipping section, the tone section and the output section. The gain and clipping is accomplished using the LM308 Op-Amp and two 1N914 diodes in a symmetrical, hard clipping configuration. The signal is substantially filtered in the Op-Amp feedback path. The tone section is a simple RC low pass filter, and the output section has some additional filtering as well as a buffer and passive volume attenuator.

For the purpose of simplifying this model, the power supply circuit and any biasing voltages or components were removed. This may have had some unintended consequences on the harmonic structure of the Op-Amp clipping, which will be addressed in the further research section.

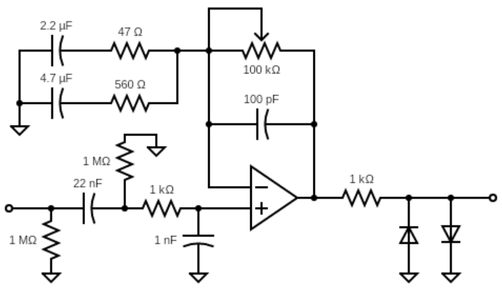

Figure 1. Simplified schematic of the Pro Co RAT gain and clipping section.

The Pro Co RAT circuit was modelled in MATLAB using the nodal Discrete Kirchhoff (DK) method [4, 5]. This method was chosen because it can be optimized relatively easily for real-time processing. The diode clipping model uses a damped Newton-Raphson solver and was 8x oversampled in order to limit aliasing and increase stability [6]. The mathematics of discretizing an analog circuit model or simulating diodes are beyond the scope of this paper.

This non-ideal Op-Amp model attempts to emulate Op-Amp behaviour, rather than simulating the components of a physical Op-Amp circuit. Each of the three non-ideal characteristics are emulated algorithmically and integrated into the Pro Co RAT circuit model at the output node of the LM308. The effects are implemented in series and can function independent of one another. This allows for greater insight into the impact of each individual characteristic on timbral quality as well as stability.

3 Slew Rate

A non-ideal Op-Amp will have a finite limit on how quickly it can adjust to large changes in voltage. This limit is referred to as slew rate. Slew rate is measured in V/µs. In practical terms, when operating at the peak voltage (9V in this case), the Op-Amp will be unable to accurately reproduce frequencies above a cut-off point. This results in a unique type of distortion. The LM308 is reported as having a slew rate of 0.3V/µs, which makes it a very slow Op-Amp, with a maximum clean frequency of approximately 5.3 kHz at peak voltage [3, 7]. The RAT is able to introduce as much as 67 dB of gain, meaning almost the entire range of the distortion knob results in the LM308 operating at the 9V peak voltage.

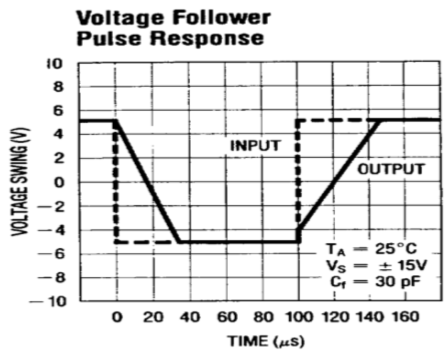

Figure 2. Step response of LM308 Op-Amp [3]

To recreate this behaviour digitally, we converted V/µs to V/sample and determined the maximum possible slope for the LM308 model. By restricting signal slope within the bounds of the discretized slew rate, we were able to accurately emulate LM308 step performance (Figures 2 and 3).

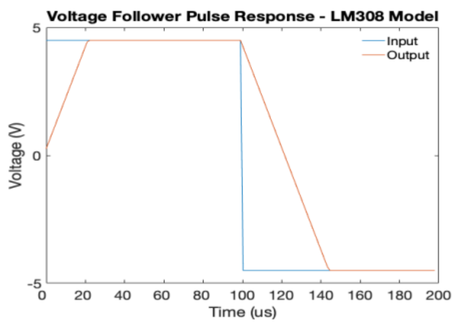

Figure 3. Step response of LM308 Model

4 Gain-Bandwidth Product

A non-ideal Op-Amp will also have a finite limit on how quickly it can adjust to small changes in voltage. This results in an upper limit of frequencies that an Op-Amp is able to reproduce. As amplification increases, the upper limit is reduced and bandwidth decreases. Gain-bandwidth product is a measure of this phenomenon. In practical terms, this behaviour results in frequency dependent gain, with frequencies within the bandwidth being amplified by the expected amount, and frequencies outside of the bandwidth seeing a significant linear decrease in amplification.

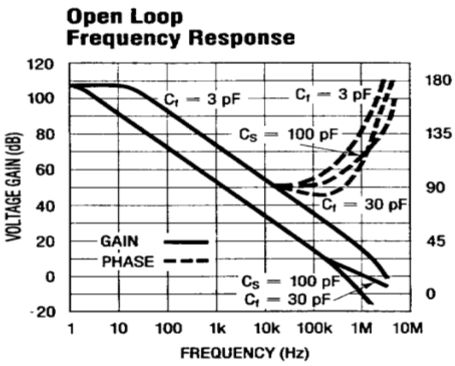

Figure 4. Frequency response of LM308 Op-Amp [3]

At maximum theoretical gain, about 67 dB, the LM308 with a 30 pF compensation capacitor has a high frequency limit of about 500 Hz. In order to emulate this behaviour, we modelled a simple RC low pass filter with a variable cut off frequency. The filter slope is 6 dB/octave which mirrors the approximately 20 dB/decade seen in Figure 4. The cut off frequency is determined by the value of the "Distortion" potentiometer.

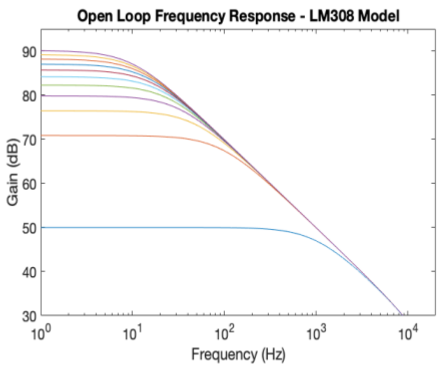

Figure 5. Frequency response of LM308 Model. The responses shown represent different positions of a theoretical gain potentiometer.

This method, while imperfect, allowed for a reasonably accurate recreation of the LM308 gain-bandwidth product behaviour. The analog filter model provided more accurate gain-to-filter tracking than other algorithmic attempts.

5 Supply Voltage

The LM308 Op-Amp is capable of being run from +/- 2V to +/- 18V [3]. For the RAT circuit, it is powered at 9V. The RAT operates with a 4.5V bias which means the LM308 is capable of accurately reproducing signals between 0 and 9V. When a signal exceeds those bounds, that signal is limited by those bounds. As stated in Section 2, the RAT circuit is capable of amplifying far beyond the 9V range, meaning that Op-Amp clipping is almost guaranteed and near constant.

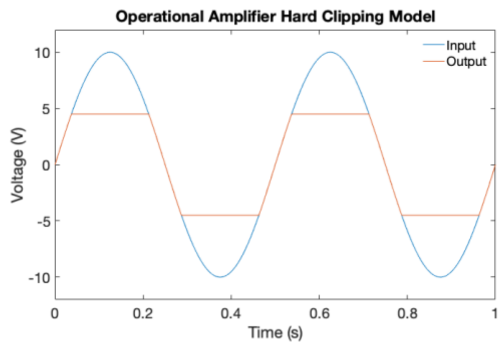

Figure 6. Clipping behaviour of LM308 Model

The LM308 is not known to exhibit any esoteric Op-Amp clipping behaviour such as phase inversion or rail-sticking, so a simple hard clipping algorithm should suffice to replicate the impact of supply voltage on output. Because we have chosen to simplify the circuit to remove the 4.5V bias current, the 9V operating range is shifted to between -4.5V and 4.5V.

6 Comparison Method

Using an Audio Precision analyzer, we compared the frequency response, harmonic content and noise of the Pro Co RAT pedal, a plugin utilizing an ideal Op-Amp model and a plugin utilizing a non-ideal Op-Amp model. the circuit analysis and architecture of the two plugins were identical, with the exception of the Op-Amp model. To match level between the hardware and software versions, a Focusrite Scarlett 2i2 was used as an interface. A 0.707V sine wave was routed into the Scarlett and then into Ableton Live. The Pro Co RAT pedal was inserted as a "plugin" using an external audio effect loop and a Radial JCR Reamp device. This allowed for easy switching between the hardware and software versions. The signal was then routed out of the Scarlett and back to the Audio Precision. For the RAT and both plugins, all measurements were taken with "Distortion" and "Volume" maximized, and "Tone" minimized. With the pedal or plugins on, 0.707V were returned to the Audio Precision.

7 Results

As seen in Figure 7, the RAT pedal exhibits a very smooth frequency response all the way up to 2 kHz, even with a maximum "Distortion" value. Frequencies over 5 kHz are diminished and drop off significantly at 10 kHz. The ideal Op-Amp model exhibited a much more jagged response with a pronounced low end. Frequencies below 1 kHz showed as much as a 6 dB increase from the RAT pedal. The non-ideal Op-Amp model seemed to have split the difference, with a much smoother response than the ideal Op-Amp model but still a 2 dB increase in frequencies below approximately 300 Hz. The non-ideal Op-Amp model also dropped off after 10 kHz.

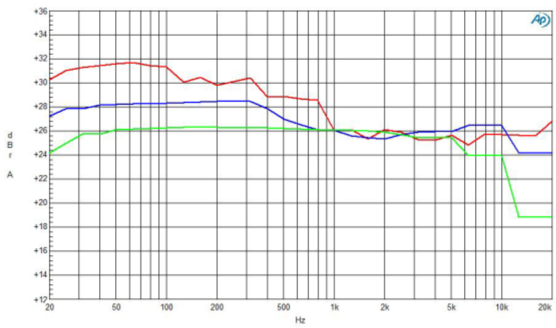

Figure 7. Frequency response of Pro Co Rat pedal (green), ideal Op-Amp model (red) and non-ideal Op-Amp model (blue). Normalized at 1 kHz.

Figure 8 shows that the RAT pedal generates both even and odd harmonics in approximately equal intensity, with a noise floor of approximately -70 dB. Conversely, both Op-Amp models generated exclusively odd harmonics. The ideal Op-Amp model seemed to have a frequency dependent noise floor, with noise diminishing as frequency increased. The floor was between -30 dB and -50 dB. The non-ideal Op-Amp model had the lowest noise floor by a significant margin: approximately -100 dB.

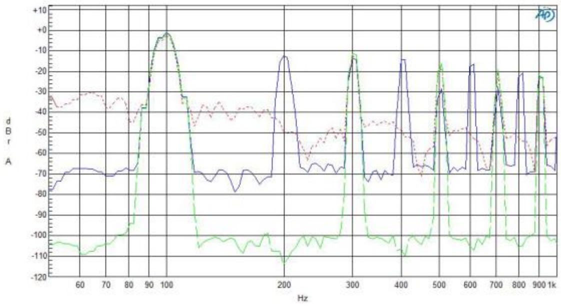

Figure 8. Harmonic distortion and noise floor of Pro Co Rat pedal (blue), ideal Op-Amp (red) and non-ideal Op-Amp (green). 100 Hz test signal.

8 Conclusions

First, the even and odd harmonic structure of the Pro Co RAT pedal was a surprise. Based on the symmetrical Op-Amp and diode clipping, odd harmonics were expected to be the vast majority. The two models reflect that hypothesis. It is difficult to conclude that our RAT model is accurate with such a large difference. However, for frequency response, the non-ideal Op-Amp model did show an improvement over the ideal Op-Amp model. The ideal Op-Amp model is much more jagged, with multiple peaks and troughs, suggesting instability within the model. Further, the non-ideal Op-Amp model outperformed both the RAT pedal and the ideal Op-Amp model in terms of noise. Once again, the high and variable noise floor of the ideal Op-Amp model suggest instability in the model.

One possible cause of this instability is the high gain of the RAT circuit. Without the limiting behaviours of the non-ideal model, the 67 dB of potential gain is fully realized. As a result, the input signal of the Newton-Raphson solver is much less predictable, likely causing instability when simulating diode clipping. In the non-ideal Op-Amp model, slew rate, gain-bandwidth product and supply voltage all work towards restricting the output of the Op-Amp. These behaviours result in a more predictable signal for the diode model, which allows for smoother frequency response and less noise.

9 Further Research

In multiple articles by Inui et al., it is suggested that power supply voltages can have a dramatic effect on the presence of even order harmonics in guitar distortion circuits [8, 9]. In order to more accurately model the Pro Co RAT pedal and its harmonic series, the power supply circuit or biasing may need to be included. Preliminary research shows that asymmetrical clipping can be achieved in the Op-Amp model by including the bias voltage in the circuit model and applying a DC offset to the Op-Amp Clipping algorithm.

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