Overdrive, Fuzz & Distortion:

investigating Range-Master, Tube-Screamer, et al.

By Wolfgang Hoenlein & Manfred Zollner

“Distortion Box” or “distortion pedal” is a name for devices that produce a 'fatter' guitar-sound with more harmonics. This is achieved by operating an amplifying system in the non-linear portion of its characteristic curve, so that the output signal receives the desired coloring of sound. More often that not, this non-linear operation will happen outside the bounds of parameters as foreseen by data sheets, and consequently results cannot be precisely calculated in advance. More important for the musician, however, is the result as it is perceived by the ear.

Basically each and every amplifier is also a distortion device by virtue of its characteristic curve that, in reality, is not linear. Even in HiFi amplifiers harmonics are added to the signal, although to such a slight extent that they are inaudible. Therefore, the magnitude of distortion is the significant factor in a distortion device, and it is this aspect that distinguishes the typical characterizations of distortion devices from each other. In ascending order of the degree of distortion the designations are boost, overdrive, distortion and fuzz.

Following the above definition one thing is clear: a good distortion device is one that is perceived by the musician as sounding good. Designing by the book cannot be the primary goal. Limits, if any, will be given to the designer only in terms of the reliable and reproducible operation of the circuit and, if battery operation is needed, a low power consumption. First and foremost goal, however, is a sound enjoyable and attractive to as many musicians and listeners as possible, thus creating a sales success for the manufacturer. Accordingly, a wealth of devices was and is available; they are often more distinguished by looks than technical differences. Still, a few main designs can be identified. As examples, we will look at two of these more closely in the following.

Transistor Distortion

Historically, early distortion devices were classical 1960's transistor circuit designs with a rather mundane exterior. As an example of a successful first generation distortion device we will look at the Range-Master marketed by Dallas Arbiter.

The Range-Master

At a glance the basic design looks much like a text-book one-stage grounded emitter circuit (**Fig. 1**). Transistors available in the early 60's were mainly of the Germanium types, with an alloyed P-conducting zone deposited on an N-conducting substrate. There was also the NPN variety, differing mainly in reverse polarity of the operating voltage. The OC-44 PNP-transistor deployed in the original Range-Master was in fact a high-frequency transistor popular at the time in view of its good availability and low price.

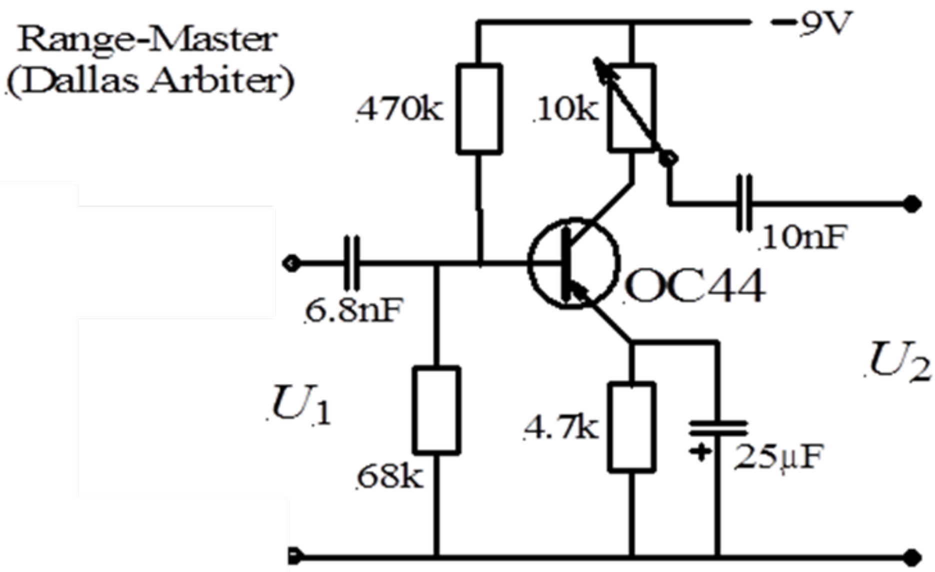

Fig.1: Circuit of the Range-Master

For operation, a transistor needs a small base current provided by the voltage divider at the base (470 kΩ and 68 kΩ). This voltage divider is set such that the larger portion of the current passes through the resistors as transverse current, and the heavily temperature-dependent base current is “attenuated”. The alternating voltage coming from the pickup is fed to the base through a 6.8 nF capacitor. Small changes of the base current caused by the input signal result in larger changes of the current passing through collector and emitter – this constitutes the amplification function. The collector resistor (a potentiometer for adjusting the output AC voltage) facilitates feeding the signal to the output via the coupling capacitor.

The emitter resistance (4.7 kΩ), though not strictly needed, provides for more stable operation since the collector current is strongly temperature-dependent, as well. Moreover, the resistor increases the input resistance of the complete circuit. However, this kind of negative feedback takes away from the overall gain. That is why this resistor is being AC-bypassed via a capacitor (25µF) in almost all audio amplifier applications – the emitter resistor's stabilizing effect on the operating point can be utilized while preserving the full amplification for the AC signal.

Let us now consider the effect the input circuitry has on the signal delivered by the pickup. **Fig. 2** shows the equivalent circuit for the relatively complicated present scenario, with the pickup represented by its inductance, internal resistance, loss resistance and winding capacitance, the cable represented by its capacitance and the input impedance of the Range-Master given by its coupling capacitor and its input resistance.

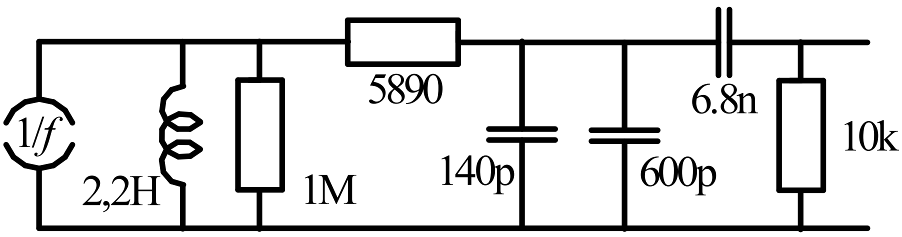

Fig. 2: Equivalent circuit of the pickup, cable capacitance and input circuit of the Range-Master

As a whole, the circuitry constitutes a high-pass filter attenuating signals below 1 kHz. The low input resistance suppresses the resonant peak of the pickup and attenuates signals above approximately 2 kHz (**Fig. 3**).

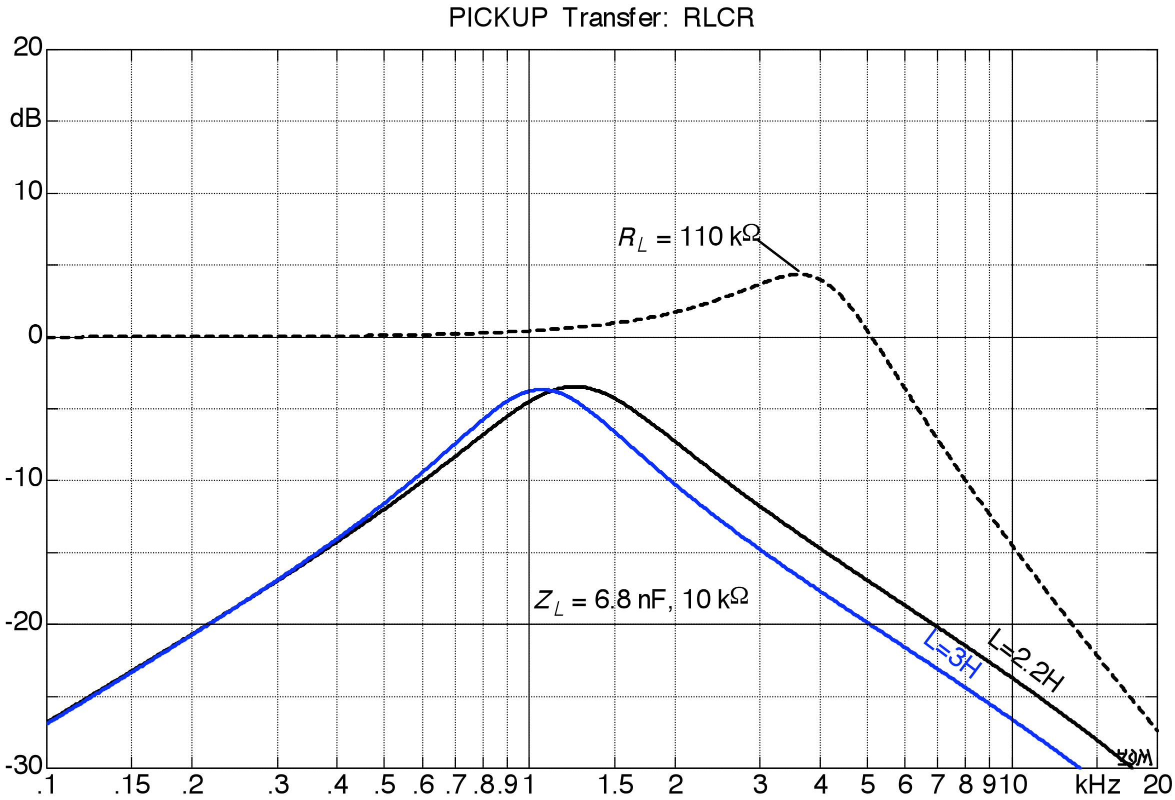

Fig. 3: Frequency response of the pickup loaded with a high impedance (top), and overall frequency response of the of pickup and Range-Master for two different pickup inductances.

The complete system consisting of pickup and booster acts as a band-pass filter tuned to the high register of the guitar. In other words, the circuit amplifies preferably medium and high frequencies of the electric guitar, which is why it is called a treble booster.

The purpose of this circuit becomes clearer once its preferred application is examined, namely purposefully overdriving of tube pre-amplifiers. Experience tells that a broad-band overdrive of tubes sounds 'muddy' and unattractive. Limiting distortion to higher frequencies sounds more pleasant. A strongly distorting amplifier generates a mix of both harmonic and non-harmonic frequencies – which is annoying to the ear especially in the bass range. Preferring amplification of higher frequencies in concert with the frequency characteristics of the amplifier following mitigates that effect. In consequence, the treble booster is best suited for amplifiers with less 'hot' input stages such as Fender Blackface models, or the VOX AC 30 without Top Boost. The distortion in the following amplifier can be precisely adjusted with the Range-Master's volume potentiometer. Moreover, the volume control of the guitar may serve to vary between lightly distorted (crunch-) rhythm sound and strongly overdriven lead tone.

So far we have run the treble-booster with low levels (by turning down the guitar volume pot) such that it was not overdriven itself, but only the tubes coming after it were. The circuit itself is not adding audible distortion in this mode of operation. Let us now turn to the case where the volume pot on the guitar is fully open, and voltages of typically 1 V and more are applied to the treble-booster's input.

The emitter resistance is so effectively bypassed by a large capacitor that the resulting high-pass effect on the bass register can be ignored. Not to be ignored is its effect on the shifting of the bias point at high signal levels causing charge reversal in the emitter capacitor: because of the non-sine shape of the emitter current the emitter voltage shifts towards the negative by about 0.2 V. The polarization voltage of the input capacitor acts accordingly: the non-symmetric base current happening with the overdrive condition reduces the average voltage at the input capacitor. These potential shift effects make up the 'secret' of the Range-Master.

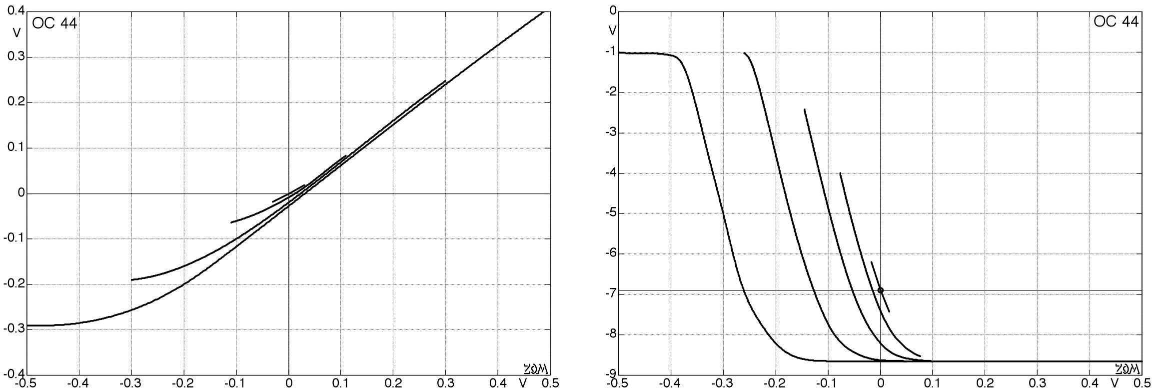

Fig. 4: Characteristic curves for Rangemaster at varying drive levels. Left: input; right: output

In its right-hand section, **Fig. 4** shows the response characteristics from the input (U_1) to the output (U_2); the bias point is marked by the crossing of the coordinate axes. At low levels the input-to-output relation is approximately linear (short straight piece of the characteristic). With the amplitude rising, the characteristic extends and bends itself, and shifts left towards more negative input voltages. The reason for this is, as mentioned above, the charge reversal of the capacitors. If the curve would not shift that would mean that already at a level of U_1 = -0.2 V clipping would occur on both sides of the wave shape, whereas the shift increases this to U_1 = -0.4 V. In other words: the shifting of the bias point causes the characteristic curve to be more asymmetric which in turn means that (for a sine wave shape) even-numbered harmonics will be accentuated. Moreover, since the bias point is drifting according to the signal level, the transmission parameters change more dynamically compared to a static characteristic, making the guitar sound more lively.

Non-linear distortion is shown in **Fig. 5** for a sine-shaped input. The negative half of the wave of the collector voltage is clipped first; the response curve is not point-symmetric, therefore the duty-cycle ratio is not 50%. In the diagram to the right the input sine has already been distorted into a near-square shape. However, the wave shape is not clipped in such a “hard” way that a square-wave harmonic spectrum would be generated.

 Translated into English by Ralf Jamer & Tilmann Zwicker

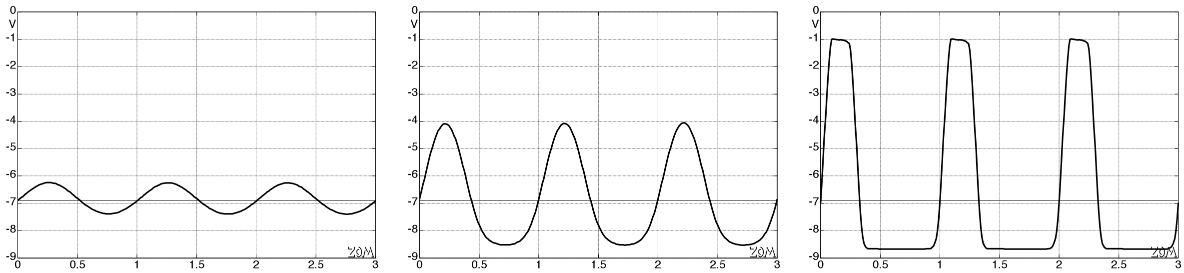

Fig. 5: Collector voltage, for different levels of sine-shaped input (f = 500 Hz)

So much for the main elements of the Range-Master distortion. Exchanging the Germanium transistor for other Germanium specimen may change the distortion effect of the Range-Master. Even for the same type, typical production tolerances in the components of early transistor technology can result in notable differences e.g. in the gain. In (playing) practice, the variation of electrical parameters of the transistors may strongly influence the interaction of the Range-Master with guitar and amp, although the distortion delivered by the Range-Master itself might play only a minor role.

Performance

In a real musical performance, and given appropriate playing, this simple circuit can create a sophisticated and lively harmonic blend composed of both the distortion generated by the Range-Master- and that of the following tube amp. That is why the booster's lack of any own tone adjustment is not generally seen as a downside. The amount of distortion can be very delicately set by Range-Master's volume control, and by the guitar volume (and possibly tone) pots. In spite of its simplistic circuitry, the Range-Master and its clones are used by many musicians still today. The BSM manufacture, for one, offers a wide palette of boosters serving the diverse needs of different players.

Do it yourself

Because the Range Master is such a simple device, DIY-ing is rewarding: either from scratch as described by Martin Thewes (r.i.p.) in “Gitarre und Bass” 4/09, or utilizing one of the many well-devised and very affordable kits available (for example from “Das Musikding”). DIY in fact is highly recommended: assembling the circuit with its low supply-voltage is not dangerous as opposed to working on a high-voltage tube amplifier, and success is almost unavoidable in view of the simple build. Also, you will obtain knowledge of inner workings of the most important amplifier designs using transistors – on the side. Needless to say modifications on DIY kits are easier done than on expensive industrial products. You will, however, also learn that a build with a stage-worthy housing is a time-consuming affair, and why pedals manufactured in small-scale batches may be expensive. The Germanium transistors may only be subjected to high temperatures for a short time when soldering them in. Sockets are a helpful here, and a good way to ensure proper seating as well as quick and easy swapping of parts while experimenting with modifications.

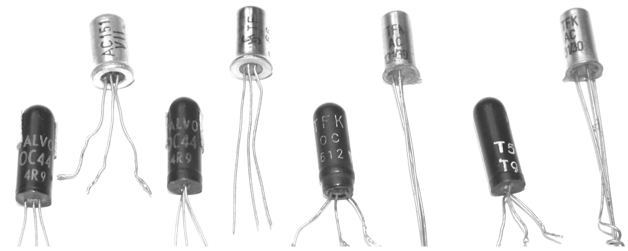

Fig. 6: Several specimen of Germanium transistors

Further Developments

It is easy to see that adding a second transistor stage will increase gain compared to the Range Master circuit, and distortion will set in earlier. A typical representative of this type would be the Fuzz Face by Dallas Arbiter which sometimes, depending on the year of manufacture, used three transistor stages (Physics of the Electric Guitar, Ch. 10.8.5.5). As the name suggests these designs produce a brutal kind of distortion (Fuzz) in which any similarity to the original signal is hardly recognizable. Even though the Fuzz Face has more controls, the sound is less malleable compared to the Range Master. That it still can be put to great musical use was impressively proved by Jimi Hendrix and others.

Diode Distortion

It turned out quickly that the response curve of a diode is an ideal instrument to generate distortion, and independently so of the drive and volume settings of an amplifier. Roughly put, a diode passes through current with the voltage applied in one direction while with opposite polarity of the voltage it constitutes a current barrier. However, in the passing direction current does not set in immediately. Using a linear representation, and being not quite exact but rather illustrative, we may speak of a threshold voltage the magnitude oif which depends on the diode materials (Physics of the Electric Guitar, Ch. 10.8.5.1). For Germanium this threshold is at 0.4 V, for Silicon at 0.7 V, and even higher (and depending on their color) for LEDs. Now, if one is to wire a diode from the signal carrying wire to ground, it will clip the signal at the threshold voltage because of the diode becoming conductive. This means clipping at diode threshold level is possible and we need not rely on clipping at the power-rail level. Moreover, the distortion-operation may be separated from amplification and tone-control stages, and more refined and subtle sound design is possible.

Combining two diodes in an anti-parallel manner will result in symmetric clipping (**Fig. 7**) The well loved "Rat" by ProCo is an example based on this principle of operation. The Rat sound is mostly named "distortion" since it packs a hefty bite. But also more subtle shades of distortion can be dialed in, qualifying it as "overdrive". How else could a fusion guitarist as sensitive as John Scofield be using the Rat?

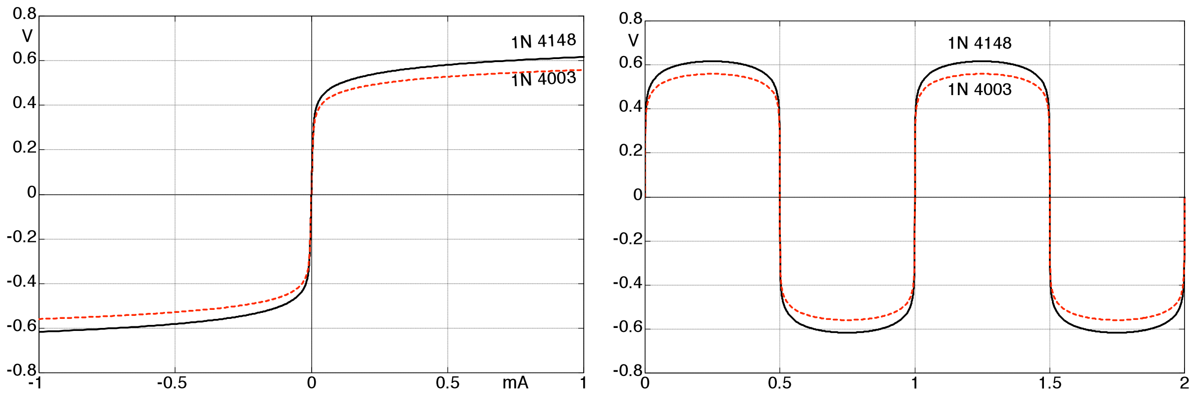

Fig. 7: Response curves of two inverse-parallel Si diodes (left) and voltage limiting for a current-stiff sine signal input (right)

Now if one combines a Silicon diode with a Germanium diode, or two serial diodes with an anti-parallel one, the result will be asymmetric distortion. It is easy to see that by combining different material diodes with resistors or even capacitors leads to a plethora of distortion configurations and sounds. Even inside of tube amplifiers (e.g. Marshall), such diode arrays have been used for (additional) distortion.

Distortion using op-amps

Once the sections generating distortion, amplification, and tone-shaping were disentangled, discrete transistors could now be replaced by so-called operational amplifiers. These "op-amps" were initially developed as early as the tube age and pack some ideal features for amplifiers. High input impedance on a differential input combined with low output impedance and very high gain, to name just a few characteristics. Supplementing an op-amp with external circuitry of suitable passive elements, amplifiers with tailor-made properties can be designed.

Since the development of integrated silicon circuits starting in the 1970's it was also possible to shrink voluminous tube designs into tiny silicon chips that fit in a housing the size of a fingernail. Nowadays, four or more op-amps fit in such a package so these are – for the circuit designers – heavenly times compared to the Range Master era. Such miniaturization is also a prerequisite to accommodate more complex designs in battery-operated "stomp boxes".

However, as can be seen with the Fuzz Face, more sophisticated circuit designs do not necessarily equal "bigger sound". The Ibanez Tube-Screamer (that recently saw its 35th anniversary) is an example of getting a more "musical" result using the new possibilities. In these times of light-speed technical development, the Tube-Screamer fells "stone-age-y", yet it marks an example for a technological end-point of the development of distortion boxes since its design concept was leading the way and keeps inspiring new variations.

The Tube-Screamer

As its name suggests, the Tube-Screamer is meant to produce a tube-like distortion as it is generally characterized as "warm" although there are no transparent evaluation criteria for it. Whether the Tube Screamer is called a distortion box, an overdrive device or a treble booster – it seems like a matter of taste more than anything.

The device was designed to be connected between guitar and amplifier, and consists of three sections: a transistor-based buffer (impedance transformer), a distortion-generating section with bass cut, and a tone filter. Fig. 8 shows the distortion-generating components based around an analog op-amp. The distorting anti-parallel diodes are in the feedback path of the op-amp. This path determines the distortion properties of the amplifier.

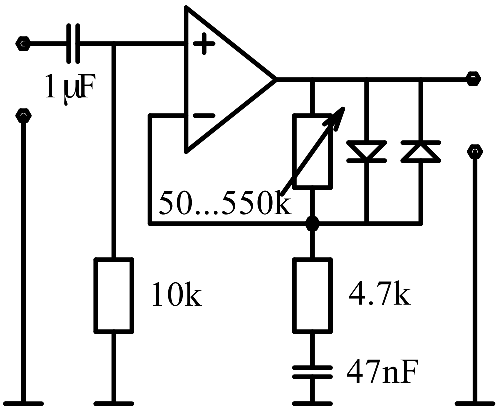

Fig. 8: Schematic of the distortion-generating components in the Tube-Screamer

First, let us look at the operation without diodes, i.e. for voltages in the feedback path below the thresholds of the diodes. The circuit now operates as a 720-Hz-highpass filter (Fig. 9).

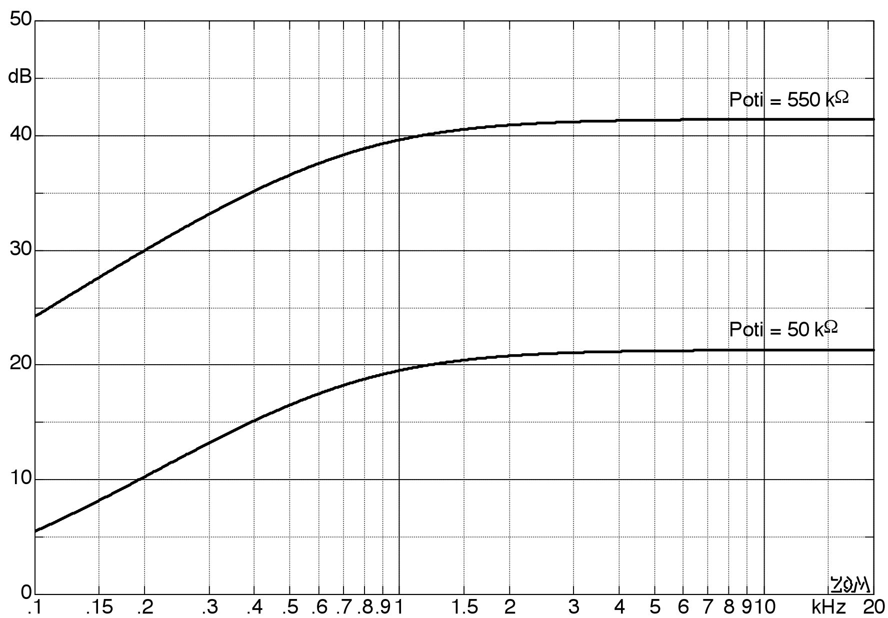

Fig. 8 Small-signal frequency response of the Tube-Screamer

Now the diodes come into play. As soon as the diode voltage is large enough to cause a notable current (relative to the potentiometer-current), non-linear distortion occurs and the voltage across the potentiometer is limited. Since the output voltage is composed of to parts (namely the voltage across the potentiometer voltage, and the voltage across the RC-2-terminal network), part of the undistorted signal is added to the mix. This is a characteristic of the Tube Screamer: not only does it distort, it mixes in the original signal, too.

The potentiometer allows to control the basic amplification in the distortion branch, but not the control of the distorted output signal, nor of the undistorted signal. There is no means to balance the original and the distorted signal portions without changing the circuit itself.

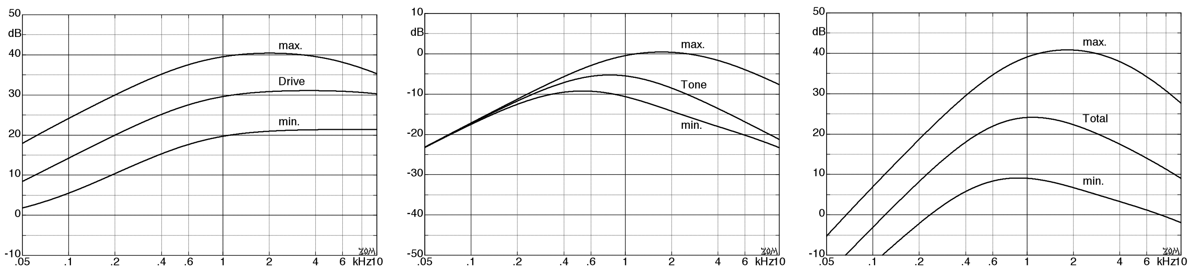

Fig. 10 Tube-Screamer frequency responses: distortion-section, filter, and overall

The frequency responses of the Tube Screamer are displayed in Fig. 10 for several potentiometer settings. Comparing them with those of the Range Master it is apparent that a similar band-pass arrangement centered around 1-2 kHz was chosen.

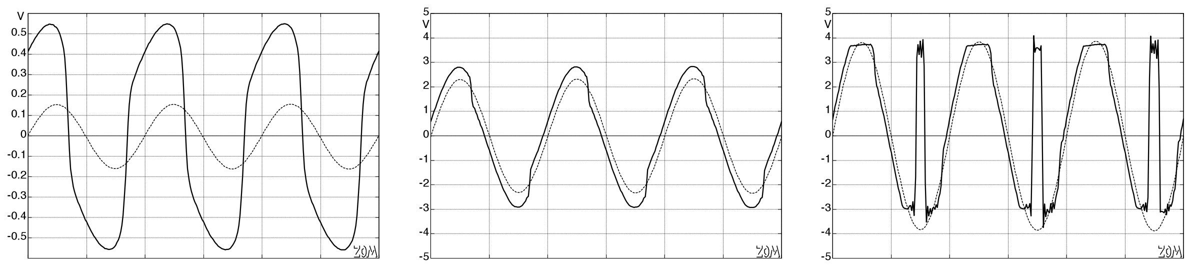

Fig. 11 Output signal for different drive-levels (500 Hz sine input).

Fig. 11 shows the time function of the op-amp output voltage for three different drive levels. The phase shift is easily noticeable – it results from the 4,7-kΩ-47-nF-network, not from the high-pass at the input. In the two sections to left of the figure, moderate distortion is seen, while the right hand plot displays a very undesirable type of distortion that is to be avoided at all cost. It stems from a breaking-through to the opposite voltage limit. The exact cause of the problem (latch-up?) is beyond the scope of this paper. A different op-amp must be used in such cases. The specimen used in these measurements was a TL072 that, being a FET op-amp, apparently is susceptible to such effects. Having said that, it should be noted that the TL072 otherwise is a very good op-amp, and the behavior just described appears only at very high levels. Nevertheless, once this happens the resulting terrible sound will be suitable only for very special uses. This is another example of the rude surprises that may happen when an op-amp is operated way outside the specifications.

Practical experience

The Tube Screamer with its circuit design has established itself as one of the most popular distortion pedals among musicians, unique and unmistakable e.g. as presented by Stevie Ray Vaughan in his Hendrix-adaptions. Much is possible, ranging from slightly driven sounds that only the following tube amp brings to full bloom, to distinct full-on distortion. On top of that the very effective tone control provides for many shades. A very successful concept indeed!

Modifications

To increase the distorted portion of the sound, two more diodes can be added, for instance: two each connected in series, and both these pairs in an anti-parallel connection. Using two diodes in one direction but only one in the other results in an asymmetrical response that sounds fuller and more assertive than the symmetric variant. Adding resistors or FETs into the diode-branch can yield a smoother, mellower onset of the distortion. Whatever you prefer is a matter of your taste, and in case of doubt components can be changed for small money. While we are exchanging diodes: a mix of Ge and Si diodes can sound very nice, too. Oh, and even LEDs are used these days by Marshall and others to obtain distortion.

Do it yourself

Building your own Tube Screamer clone from the ground up e.g. on strip board is recommended to experienced DIYers only because of the complexity of the circuit. The components not mentioned here and the variety of control elements will make a build from scratch a tiresome and error-prone affair. On the other hand, there is a wealth of DIY kits (e.g. from “Das Musikding”) that are both affordable and most likely to work well. Counting in a pre-drilled housing in Tube Scream-ing green and suitable knobs, one can get away with a stage-worthy pedal for as little as 40 EUR for – including your favorite mods and a very personal flavor, too.

Sources: figures taken from: M. Zollner, Physik der Elektrogitarre.

(Short) **bibliographic** (download of articles possible):

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- monthly column “Do it yourself” by Martin Thewes:
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Manufacturers:
Booster: BSM - Finest Treble Booster (www.treblebooster.net)
DIY kits: Das Musikding (www.musikding.de)

