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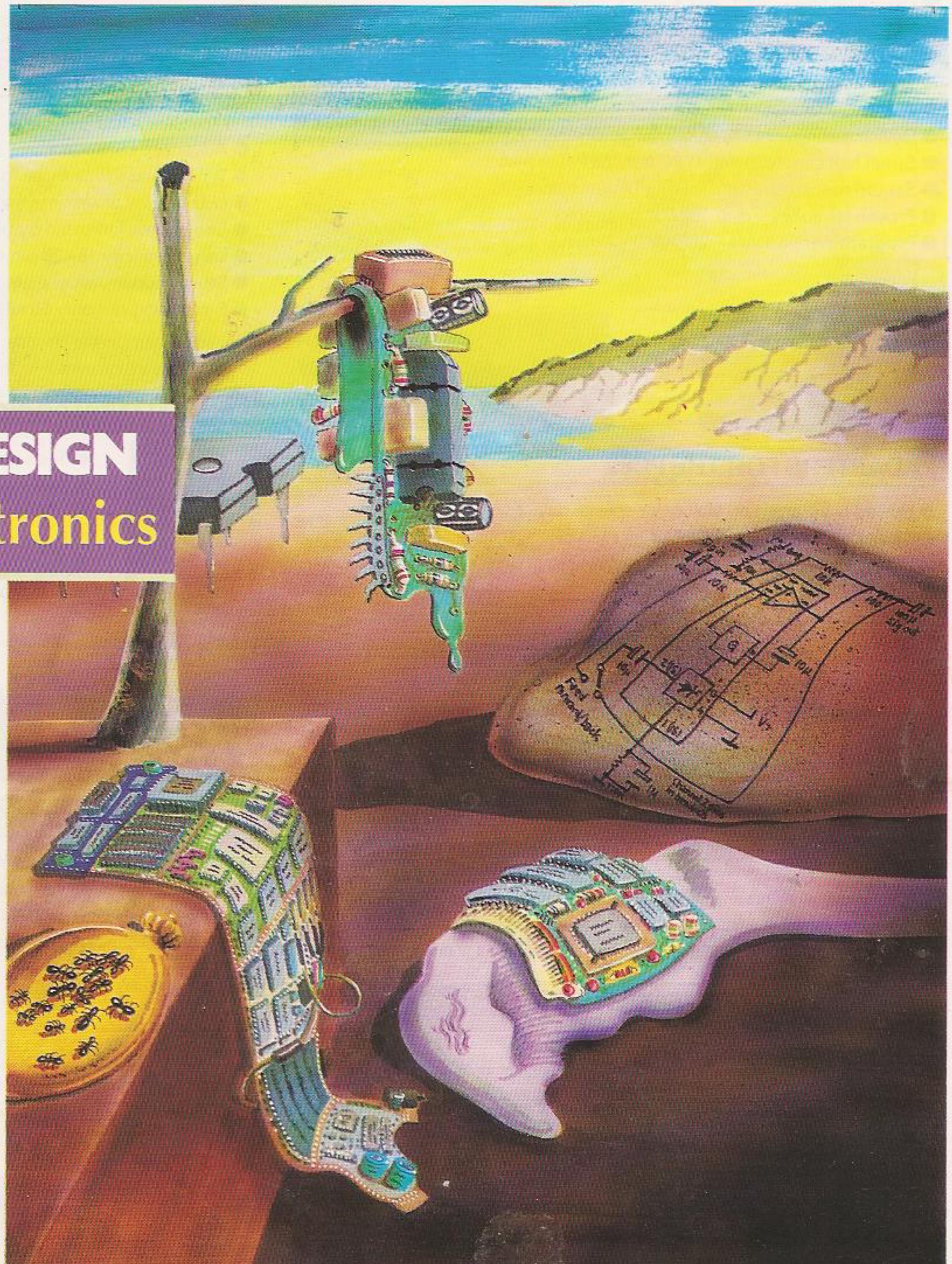

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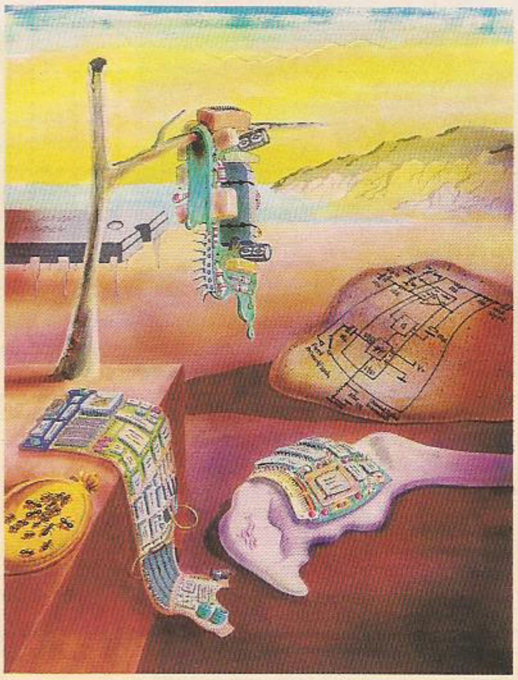
The twisted world of non-linear electronics



It is not such a big step to go from light bulbs into chaos. **Dan Ayers** *takes a look at both positive and negative aspects of non-linear components and circuit techniques.*

Turn on an incandescent filament light bulb. Doubling the voltage across a bulb certainly does not double the current since a hot filament has a markedly higher resistance than a cold one. The common light bulb looks to the supply rather like a constant current source. This non-linear behaviour is found throughout electronics and is sometimes a curse, sometimes a boon.

A low current bulb may be used to stabilise an *RC* sine wave oscillator. Ideally, a Wien bridge oscillator requires an amplifier with a gain of exactly three, which in the basic circuit of **Fig. 1a** is determined by $1+R_b/R_a$.

In practice, small errors are unavoidable so the gain is chosen to guarantee oscillation and a non-linear element is introduced to gently keep the sine wave from drifting up to its clipping limit[1]. A low-current bulb serves this purpose cheaply, **Fig. 1b**, but devices that need less current are preferable.

In effect, the bulb acts as a voltage-dependent resistor: as voltage across it increases, so does its resistance. An alternative VDR, **Fig. 1c**, rectifies and smooths a sample of the oscillator signal. The resulting voltage controls the drain-to-source conduction of a fet in turn controlling the amplifier's gain.

The non linearity is the semiconductor junction often perplexes circuit designers. Obviously there is a great difference between a diode's forward and reverse-biased resistance but in non-linear circuit design, the relationship between the diode's forward voltage and current is much more interesting. Incrementing forward voltage in linear steps increases current flow exponentially over a usefully wide region.

Figure 1 shows a diode network for stabilising a Wien oscillator. Unlike most stabilising methods which take several cycles to react, diode control is instantaneous, but this brings the penalty of introducing distortion. In many low-distortion designs, a positive-coefficient thermistor acts in the same way as the light bulb of Fig. 1b while, in other designs, an NTC thermistor replaces feedback path R_b.

Waveform synthesis

Tuned-feedback sine-wave generators like the Wien bridge oscillator may suffer from capacitor leakage and matching problems, especially at low frequencies. They can also produce an annoying bounce when their frequency is changed.

Simple square or triangle waveforms can be filtered to remove harmonics but this filtering creates a profusion of design problems. There is however another way of subtracting harmonics without filtering. It involves non-linear techniques and although it follows the same principle as digital synthesis from a sine wave lookup table, it is less complicated in practice.

The output from simple triangle wave oscillator may be passed through an exponent circuit to produce a passable sinewave. Waveform accuracy largely depends on how closely the 'bending' circuitry approximates the sinusoidal shape. Since the process is not a function of frequency, it doesn't exhibit bounce or other amplitude related problems. This technique is found in several function-generator chips, including the *8038* and *XR2206*.

There are basically two wave shaping methods, one using inherently non-linear components, **Fig. 2**, and the other relying on approximating the wave by a series of straight lines, **Fig. 3**. Both have numerous applications.

Frequency plots for instrumentation are usually shown as decades or octaves rather than on a linear scale. In the case of a network analyser, this requires a sweep oscillator with a ten or two-fold increase in frequency for a unit increase in control voltage.

Conditioning a linear control input via a buffered diode provides a suitable non-linear characteristic through the diode's exponential *V/I* relationship. A better option is to use the V_{be} to I_c exponential relationship of a standard junction transistor. Temperature errors can be reduced by a long-tail pair and temperature-

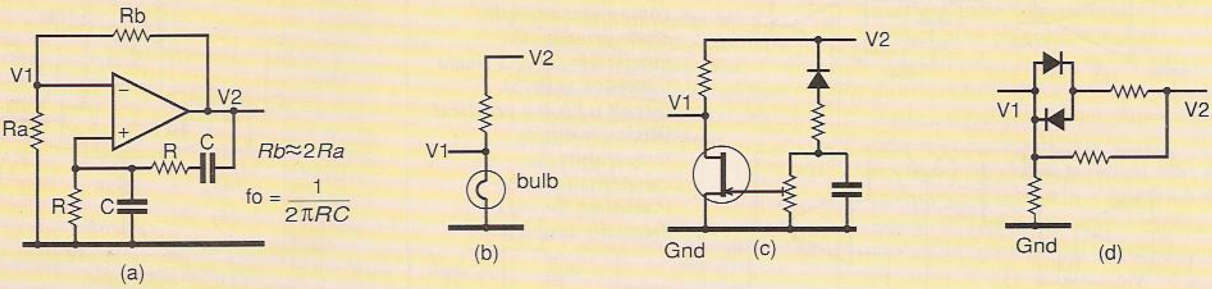


Fig. 1. In basic Wien bridge oscillator, (a), amplitude can be stabilised by replacing Ra, Rb with non-linear networks. Low current lamp acts as a VDR, (b), and a fet as a voltage-controlled attenuator, (c). In (d), diodes provide non-linear feedback.

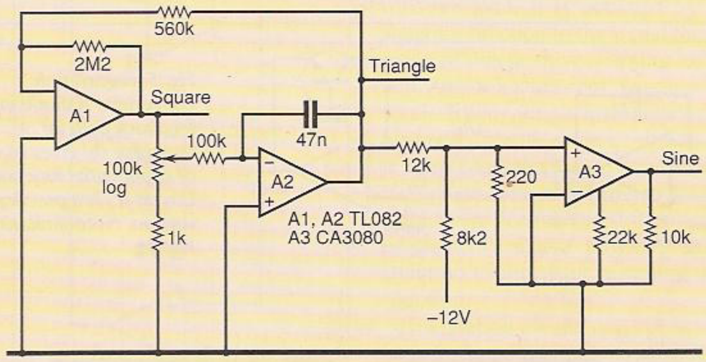


Fig. 2. Function generator synthesizes sine wave from triangle using transconductance amplifier A3 biased into non-linear region. Tweaking resistors around IC3 can give better than 2% purity.

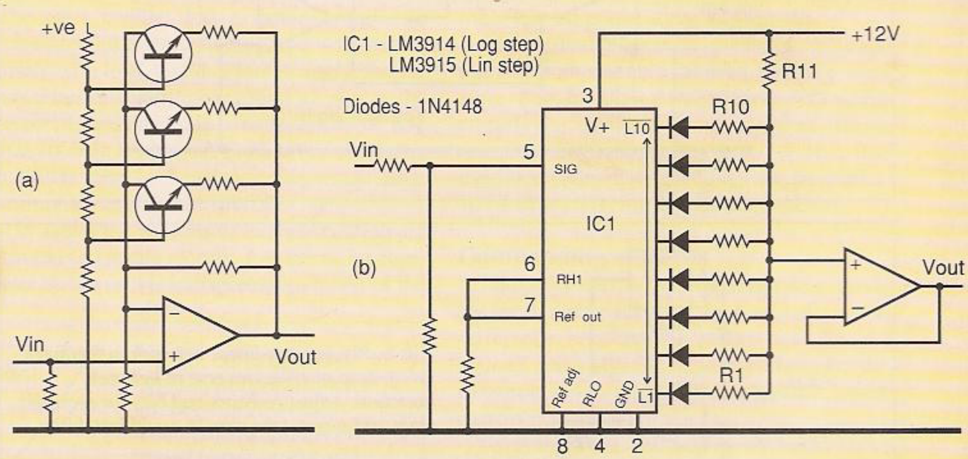


Fig. 3. Piecewise approximation to a non-linear function. In (a) transistors successively turn on as input voltage increases. Base resistors determine break points, emitter resistors determine slope. Bargraph chip, (b), gives 10 breakpoints. It must be used in bar mode. Resistor ratios determine slope.

dependent resistor, R_T of **Fig. 4**.

Early analogue music synthesisers relied on combinations of voltage-controlled modules. Since music is almost entirely based on octaves, the modules needed exponential converters to modify the linear control voltage supplied from keyboards or sequencers. Convenience dictated that the converters were exponential current sources or sinks for current-controlled oscillators or filters.

In audio, the ear's non-linear response renders linear peak-level meters very difficult to interpret. Levels need to be indicated on decibel scales so that sound pressure change ratios can be evaluated in terms of equivalent change ratios in subjective loudness.

On a decibel scale, the relationship between the signal level and the scale's indication is logarithmic. Log converters can be formed by inserting a subcircuit with exponential characteristics in the feedback path of an op-amp, **Fig. 5**. Generally, the inverse of the logarithm function is obtainable by simply inserting the log converter in the feedback path of a further op-amp, **Fig. 6**. Remember that you cannot apply negative voltages to the two-quadrant log converter.

Testing for non-linearity

Linearity of DC-coupled systems is analysed by plotting output voltage or current against input by various means. With AC circuits, the usual approach is to drive an amplifier with a pure sine wave and look for distortion on the output having notched out the drive signal fundamental component. This leaves distortion products plus noise.

A linear circuit might preserve a sine wave's shape, but it might also modify its phase or amplitude (dynamic range modifiers are described later). Close examination is possible by analysing the original sine wave via a notch filter. Any non-linearity adds frequency components at multiples of the fundamental input frequency – i.e. harmonics.

Bipolar transistor audio power amplifiers suffer mainly from third-harmonic components originating at crossover and odd harmonics due to clipping. Valve amplifiers, with their 'soft' overload characteristics, tend to produce predominantly low-order odd and even harmonics due to their different non-linear characteristics. This makes an overdriven valve audio amplifier sound subjectively 'warmer' than its bipolar counterpart.

Field-effect transistors feature non-linearity characteristics close to their valve counterparts. Under certain conditions they provide a mathematical squaring function[2] that causes a notable form of harmonic distortion. Feeding the circuit of **Fig. 7** with a sine wave frequency of f results in an output frequency of $2f$ since

$$\sin^2 x = \frac{1}{2}(1 - \cos^2 x)$$

This square law can also be used to multiply the value of two voltages together

$$xy = \frac{(x+y)^2 - (x-y)^2}{4}$$

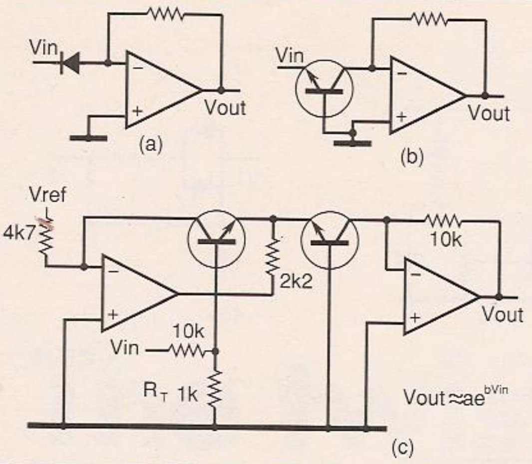


Fig. 4. Exponential converters: a simple diode provides the function in (a) or a single transistor as in (b). Circuit (c) is the practical version featuring temperature compensation. The transistors should be thermally coupled.

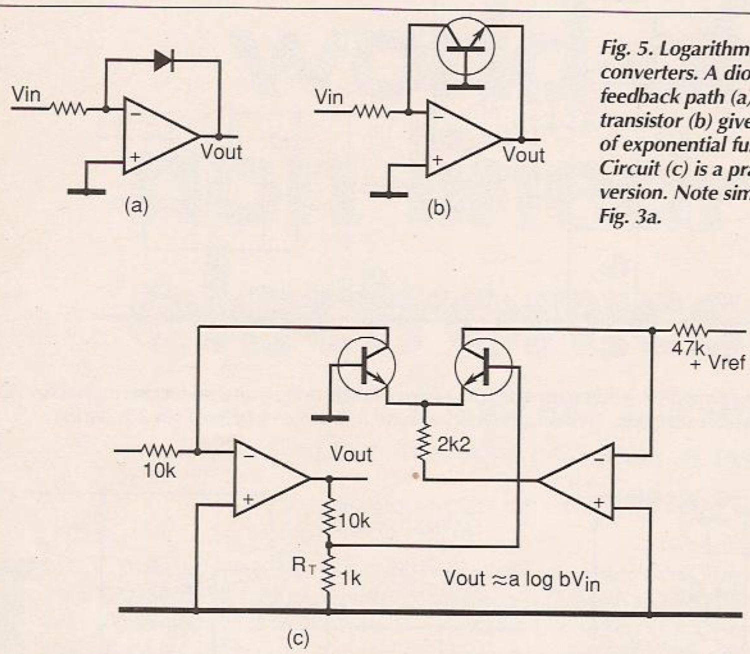


Fig. 5. Logarithmic converters. A diode in feedback path (a) or transistor (b) gives inverse of exponential function. Circuit (c) is a practical version. Note similarity to Fig. 3a.

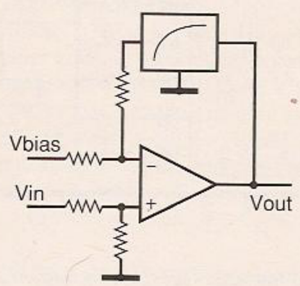
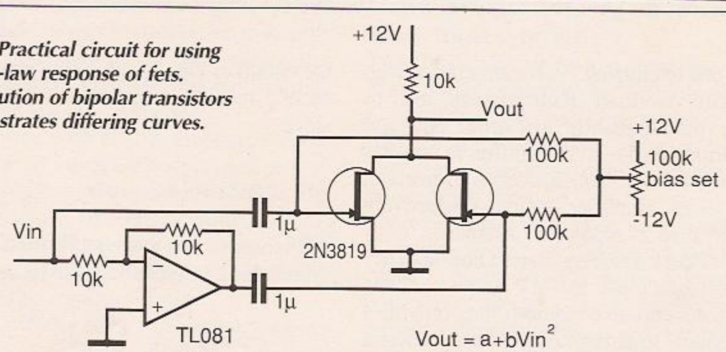


Fig. 6. Placing non-linear network in feedback of op-amp provides inverse of network function. Adjust resistors and bias for required gain and offset, take care to avoid instability.

Fig. 7. Practical circuit for using square-law response of fets. Substitution of bipolar transistors demonstrates differing curves.



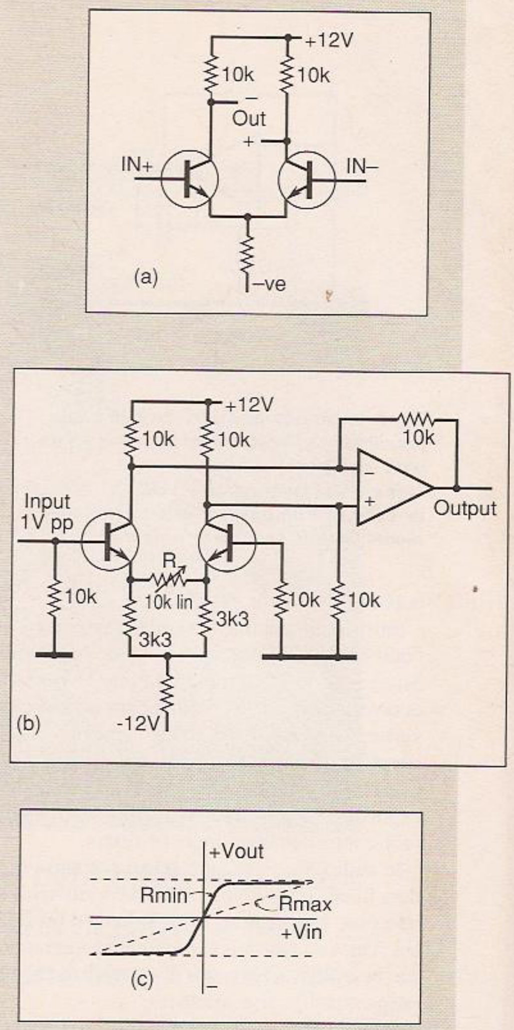


Fig. 8. Basic long-tail pair configuration (a) has non-linear characteristics for large signals. Practical circuit (b) allows control over non-linear response, from linear (R minimum) to tanh (R maximum).

Basic long-tail differential pairs, **Fig. 8a**, behave non-linearly for large signals[3]. For an input varying from below about –50mV to +50mV, output changes rapidly between two fixed output voltages, following a tan*h* transfer function[4].

Fig. 8b stretches the crossover region and varying the link between emitter currents via the potentiometer allows a range of functions from linear to tan*h*. This practical circuit was developed to simulate valve amplifier soft clipping for a guitar effects pedal. Altering the bias voltages and substituting fets may provide an even closer imitation. The *CA3080* of Fig. 2 performs in the same manner.

Gain of the long-tail pair is controlled by the tail current[3] so the circuit acts as a current-controlled amplifier. If tail current is derived from the input signal in some way, a whole range of non-linear functions become available.

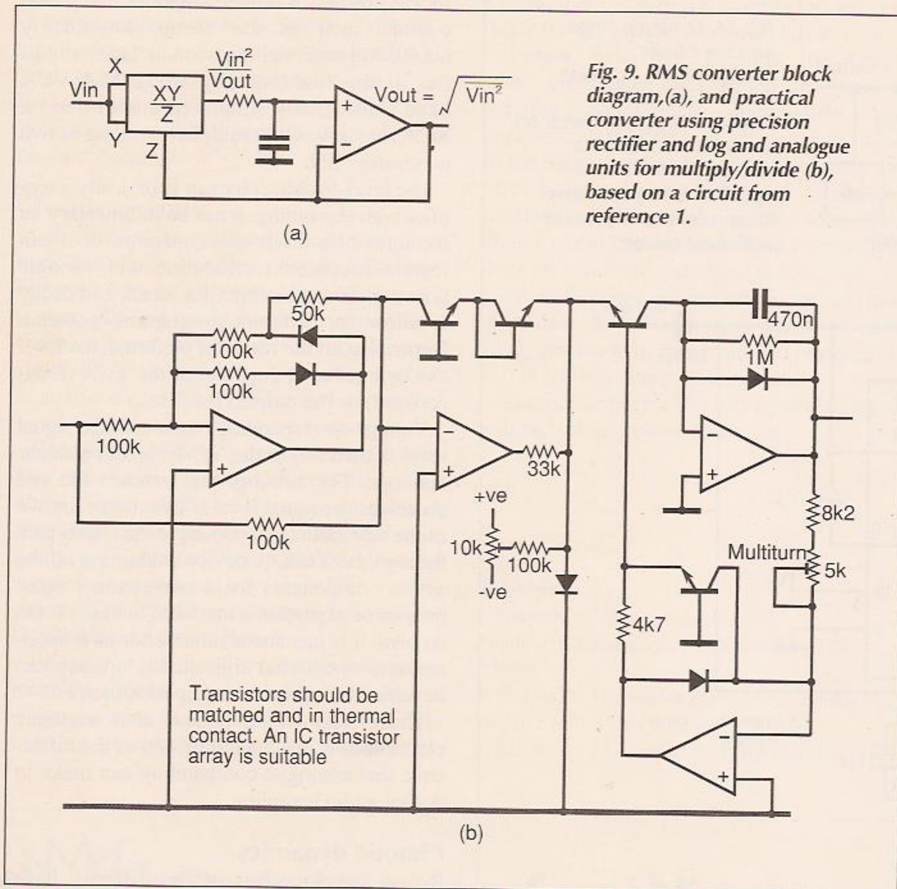


Fig. 9. RMS converter block diagram,(a), and practical converter using precision rectifier and log and analogue units for multiply/divide (b), based on a circuit from reference 1.

Intermodulation

Feeding a non-linear circuit with a signal containing two sine waves at frequencies f_1 and f_2 results in an output including not only the two input frequencies but also a proportion of their sum and difference. This type of distortion is most undesirable for audio engineers as the extra frequencies present are not harmonically related to the input and therefore subjectively most noticeable and unpleasant.

In such circuits, the instantaneous level of one signal effectively modulates the other, hence the name intermodulation distortion. The ear's cochlea has a similar non-linear response and distorts in the same way, particularly with loud sounds[5]. Interestingly, the ear has a curious non-linear effect known as the restored fundamental. If two signals of 800 and 1000Hz are played, the listener also hears a 200Hz tone - a frequency that would have harmonics at 800 and 1000Hz.

In audio, the benefits of intermodulation are limited to special effects. For the radio engineer however it is indispensable. If one of the signals is a constant RF wave and the other music, the result is a modulated RF signal as used for radio communication[6].

Multiplier chips like the *LM1496* are full of long-tail pairs and carry out modulation in a more controlled way. When used for modulating a signal, or demodulating it by the same principle, such multipliers are known as mixers to the RF engineer; when shifting the frequency of a modulated signal, they are also known as converters. Audio engineers may be more familiar with the name ring modulator.

RMS measurement

The RMS signal level corresponds to average power dissipated when a signal is feeds a resistive load. It is obtained by applying a squaring function to the signal then taking the mean of this positive, varying level and then applying a square-root function to the DC result. By juggling a little algebra, it is possible to produce the same result with a reduction in circuit complexity and associated error, **Fig. 9**. Purpose-built chips provide the function but the discrete version can still offer a more economical alternative provided that you pay attention to transistor matching and thermal coupling.

If a section of the *V/I* curve of a device 'doubles back' on itself, i.e. as voltage increases, current decreases, the device is said to exhibit negative resistance, more correctly called negative differential conductance[7]. This characteristic allows several electronic building blocks to be constructed with a surprisingly low component count, **Fig. 10**.

Tunnel diodes and Gunn devices are two-terminal components exhibiting negative resistance. Suitably biased and connected they will amplify or oscillate up to microwave frequencies. For frequencies from DC to a few megahertz, negative resistance can be synthesized with conventional semiconductors.

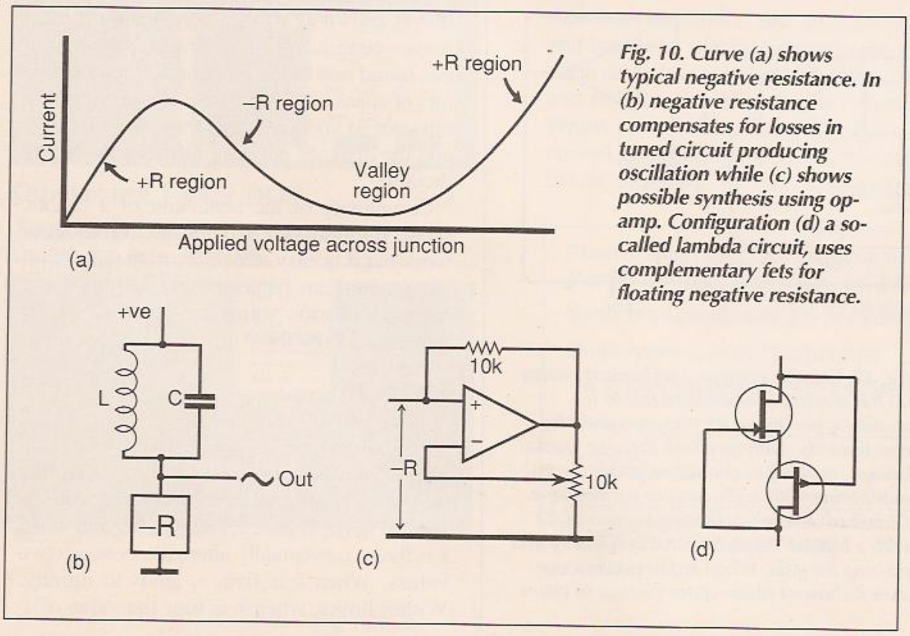


Fig. 10. Curve (a) shows typical negative resistance. In (b) negative resistance compensates for losses in tuned circuit producing oscillation while (c) shows possible synthesis using op-amp. Configuration (d) a so-called lambda circuit, uses complementary fets for floating negative resistance.

Companding systems

In audio systems, it is often desirable to modify the dynamic range of the material, i.e. the difference between the softest and loudest sounds. On magnetic tape for example, the dynamic range normally available is much narrower than that of the ear.

To maintain a reasonable signal-to-noise ratio, it is possible to compress the signal on recording and expand it again on playback. Since the range of numbers between 0 and 1000 compresses to a range of 0 to 3 logarithmically, it is not surprising that audio compression and expanding – companding – involves similar non-linearity.

The common system for altering the dynamic range of a signal makes use of three basic elements – a voltage-controlled amplifier[8], a level tracker to extract the existing dynamic information of the signal, and circuits to change the resulting information into a control voltage used by the amplifier to impose the new characteristic onto the original signal.

Except for crude speech-quality systems, where simple fet attenuators suffice, it is rarely necessary to use discrete transistor circuitry

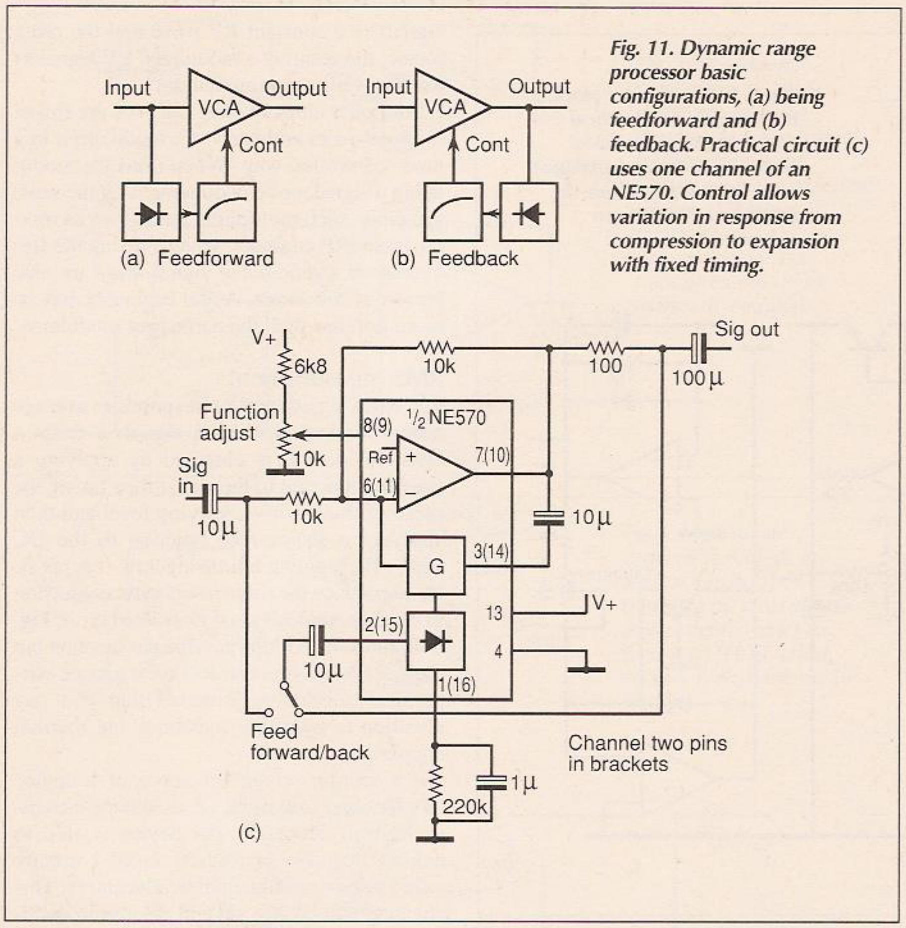


Fig. 11. Dynamic range processor basic configurations, (a) being feedforward and (b) feedback. Practical circuit (c) uses one channel of an NE570. Control allows variation in response from compression to expansion with fixed timing.

for the voltage-controlled amplifier. Integrated circuits such as the cheap, low-fidelity *CA3080* operational-transconductance amplifier or the studio-quality *dbx 2150A* VCA have considerably simplified circuit design. VCAs are a form of multiplier working in two quadrants only.

The level-tracking element is basically a rectifier with smoothing. It can be rudimentary, in the form of a diode and capacitor, or it can feature precision rectification and variable time constant smoothing for attack and decay to allow for different programme material. Depending on the response preferred, the level can be tracked at the input of the VCA (feedforward) or the output (feedback).

Voltage corresponding to the average signal level is then fed to the VCA via a non-linear network. The circuitry that extracts the and processes the signal level is commonly known as the side chain, as opposed to the signal path through the VCA. A device containing all the active components for a two-channel compressor or expander is the *NE570*, Fig. 11. On its own, it is just about suitable for hi-fi applications; an external high-quality op-amp can be added to improve noise performance[9].

Those who would believe that analogue electronics is dead should listen to the difference that analogue companding can make to digital audio sampling.

Chaotic dynamics

Recent developments in chaos theory have inspired a fresh look at non-linear dynamic systems. A physical example of such a system is a mass on a spring with a non-linear elasticity, **Fig. 12a**.

When the system is driven by sinusoidal vibrations, the mass might oscillate periodically in slightly distorted fashion at a rate related to the frequency of the driving force. If the drive frequency is changed a little however, the oscillation might stay at the same frequency, move to a different related frequency or become irregular and aperiodic.

The sequence of motion the mass moves into is known as an attractor. When the mass moves continually in an irregular manner, it has found one of the so-called strange attractors of chaos. The qualitative change from one attractor to another is known as a bifurcation and the distance between bifurcations is predictable[10].

Complexity of the behaviour of a chaotic seems to imply that inexplicable forces are at work but it is easy to demonstrate that a simple system can behave chaotically. Take a logistic equation sometimes used to model population growth,

$$x_{t+1} = kx_t(1-x_t)$$

At a given time, x_t, population is a function of that of a previous instant, x_{t-1}. Assuming that x_0 is initially 0.1 and k is one, x_t tends to zero. When k is two, x_t tends to 0.5 and when k is three, x_t eventually alternates between two values. When k is five, x_t tends to infinity. Within limits, when k is four the value of x_t

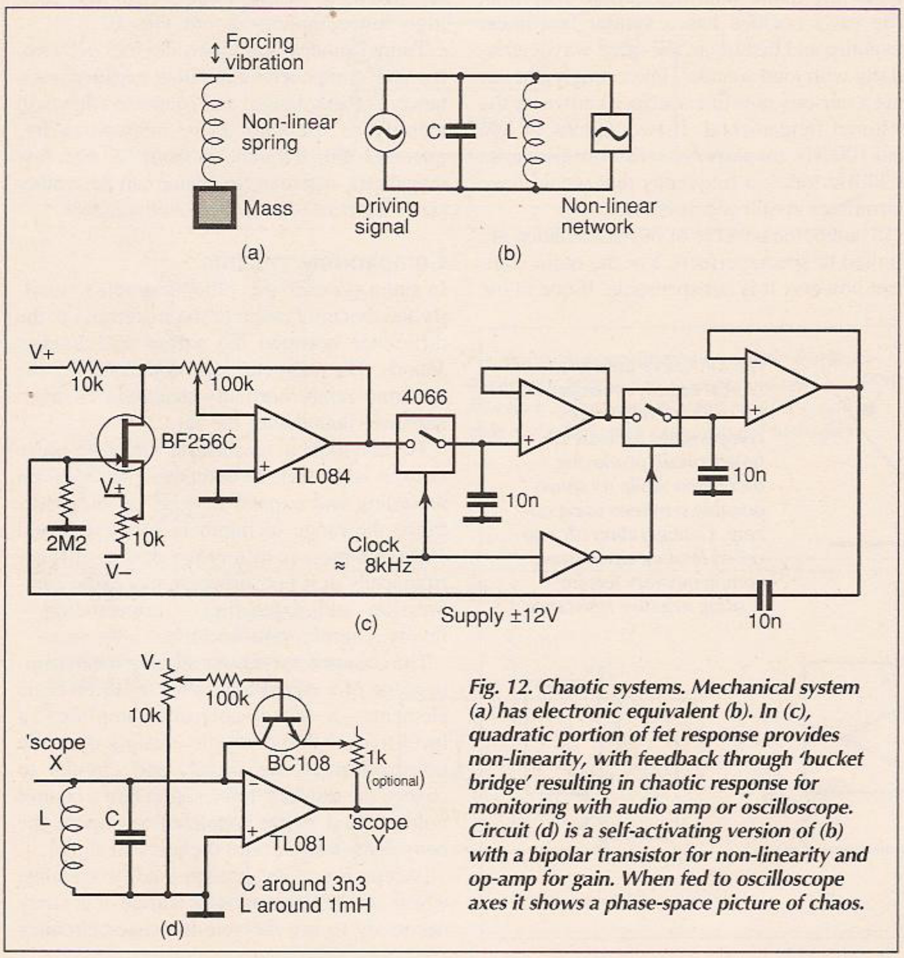


Fig. 12. Chaotic systems. Mechanical system (a) has electronic equivalent (b). In (c), quadratic portion of fet response provides non-linearity, with feedback through 'bucket bridge' resulting in chaotic response for monitoring with audio amp or oscilloscope. Circuit (d) is a self-activating version of (b) with a bipolar transistor for non-linearity and op-amp for gain. When fed to oscilloscope axes it shows a phase-space picture of chaos.

seems to vary randomly and a simple quadratic has produced chaotic behaviour. Making a small change to the initial conditions soon leads to a radically different sequence of values, showing the 'butterfly effect' of sensitive dependence on initial conditions found in all chaotic systems[11].

Chaotic circuits

In electronics, a non-linear circuit with feedback can easily produce chaotic behaviour. **Figure 12c** is an approximation of a logistic system. To get an idea of the nature of a chaotic system, it is possible to monitor most systems in phase space by connecting the horizontal and vertical amplifiers of an oscilloscope to different parts of the system.

Going back to the physical system of a mass on a non-uniform spring, a direct analogy is a tuned circuit with non-linear reactances. A non-linear reactance can be synthesized quite easily with standard components[12], but the simplest arrangement I have found for creating chaotic signals uses an op-amp to maintain the oscillation of a tuned circuit.

Because of the non-liner feedback arrangement, the oscillation produced by this circuit is chaotic as often as it is periodic, **Fig. 12d**. The inductor shown should be a few millihenries. I found that 100 turns on a ferrite rod was adequate but it played havoc with Radio 4.

Chaotic behaviour possibly lies behind many previously unexplained and partially explained phenomena – particularly where aperiodic signals such as $1/f$ noise are found. In the light of chaos theory, analysis may also offer insight into the behaviour of negative resistance oscillators – from those using Gunn diodes to unijunction relaxation circuits with their probabilistic switching points.

No component is perfect. Resistors have thermistor characteristics, diodes act as varistors... you name it. As a result, no practical circuit is entirely linear. If a circuit features amplification and feedback, chaos will be lurking round the corner. ■

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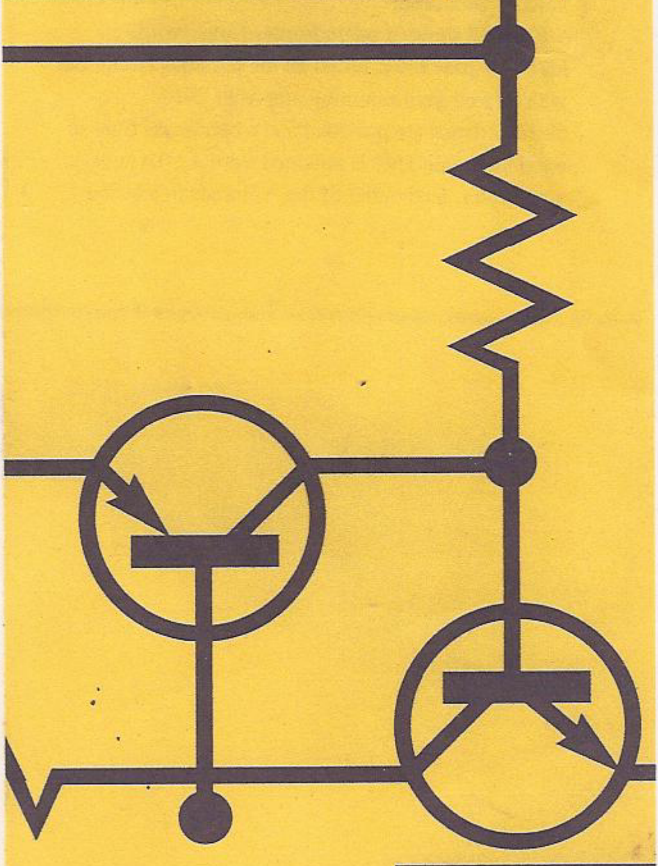

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Signals in chaos

Using a bipolar transistor as a feedback element as in Figure 1, in conjunction with a few passive components, produces a logarithmic function. Since the circuit is unstable, it is usable in a "chaotic" signal generator to give an output which, although not white noise, has a similar nature when heard.

Figure 2 shows such an arrangement. The output from the Figure 1 circuit is delayed by the phase shift of the filter and fed back to the input, whereupon a continuous oscillation is set up. Varying R_5 alters the characteristic of the basic block; some settings give a

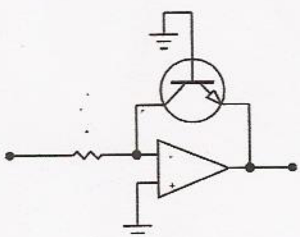

Figure 1. Circuit often described as a logarithmic amplifier, which is inherently unstable.

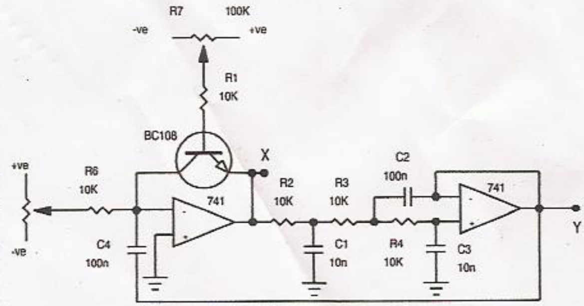

Figure 2. Chaotic signal generator uses Figure 1 circuit and phase-shifted feedback.

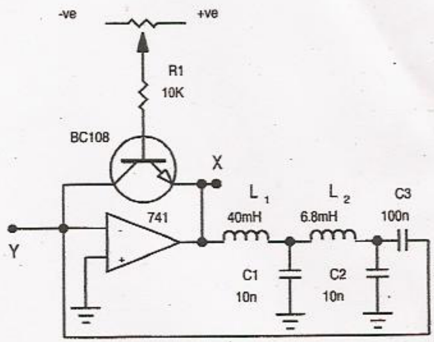

Figure 3. Simpler circuit gives same result as Figure 2, but some inductor tweaking might be needed.

periodic waveform at X, but most give a non-periodic output. Fine adjustments are possible by $R_{6,7}$, which may be omitted altogether, if desired. When set to give a "chaotic" output, the circuit is well-behaved in a chaotic sort of way and gives a continuous signal. Its behaviour becomes clear if X and Y signals are applied to the X/Y plates of an oscilloscope.