The versatile world of OTAs

Operational transconductance amplifiers can introduce programmability into almost any conventional fixed gain circuit. Multipliers, VCAs, VCOs and voltage controlled filters are all in the design repertoire. By Dan Ayers.

In the pre-semiconductor days, a figure quoted for valves was the ratio of change of anode current to change of grid voltage. This value was known as mutual conductance ($g_m$), and allowed the designer to predict the current or voltage gain of a particular circuit. Owing to the prevalence of voltage in, voltage out building blocks, transconductance (now quoted in Siemens, S), is only occasionally encountered. This is rather surprising when one considers that transistors are essentially voltage in-current out devices.

The $g_m$ model of the transistor, derived from the hybrid-pi model, is shown in Fig. 1. In common-emitter mode, the base receives an input voltage which the transistor converts to a current at the collector. This current is usually fed into a resistive load, thus giving a voltage output. One can therefore consider the $g_m$ of a transistor as a figure of merit, related to the $h_{fe}$.

Since the $g_m$ is roughly proportional to the emitter current, it follows that if we supply the emitter current with another voltage to current converter, we have a voltage controlled gain cell. The simplest version of this is shown in Fig. 2a. Despite having a limited operating region, this arrangement lends itself to rf modulation when loaded with a tuned circuit to discriminate the desired product.

Extending the transconductance principle a little further yields the operational transconductance amplifier (OTA). In general, an OTA is an op-amp whose output current is proportional to the voltage difference between the input pins. An extra pin ($I_{pin}$, $I_{bias}$, or $I_{ref}$) on OTA chips allows variation of $g_m$. An OTA with a resistive load can be considered to be an op-amp with open loop gain $A_{op} = \frac{g_m R_{load}}{R_{load}}$

Figure 2b reveals how a simple OTA operates. A long tail pair, LTP, provides differential input, as in a conventional bipolar op-amp. Two current mirrors, $M_1$ and $M_2$, serve as active loads for the input transistors. Current into $M_2$ is directly echoed to the output, whereas the current from $M_1$ is mirrored again to give a single ended output. The current from mirror $M_2$, set by the control input, determines the emitter current of the input pair, and consequently the gain. A functional diagram of an ideal OTA is shown in Fig. 3.

IC transconductance amplifiers

The CA3080 OTA owes its longevity to simple but versatile design. Devices such as the LM15700, Fig. 4, have significantly better specifications. The internal circuitry of the CA3080 differs only a little from that of Fig. 2b, and adds significant harmonic distortion to signals above a few tens of millivolts. The cir-
cut of Fig. 5 produced the transfer function of Fig. 6, which has a curve remarkably close to a section of the sine function, making the circuit useful as a triangle to sine wave converter.

Low distortion from the CA3080 is usually achieved by attenuating the signal before the device and using subsequent stages to restore the amplitude. An undesirable byproduct is a degradation of the signal to noise ratio. This distortion/dynamic range problem has been partially tackled in the LM13700 which has a diode network to linearise the chip’s response for larger signals (10dB improvement in s/n referred to 0.5% THD). The same device also includes two darlington pairs, whose collectors are internally connected to the positive supply pin. These can act merely as buffers or play a more active role in circuits as separate gain elements.

Practical applications
The current output of OTAs make them ideal for circuits involving signal summing. One can simply wire the outputs of separate devices together to share the same load. The summing and gain control capabilities of OTAs are perfect for the core of a multiplexer, where applying a current to the appropriate control pin selects one of several inputs. The CA3080 has an extra benefit here: its standby power demand is only 10µW.

The 50V/µA slew rate of OTAs makes them usable for high frequency amplification and switching applications. The current output also simplifies impedance matching to cables as the OTA load is the output impedance. Since the gain may be remotely set, it is straightforward to design voltage controlled amplifier circuits such as Fig. 7b. A few extra components bring the linearizing resistors into play as in 7b. This modification can be made to any of the following LM13700 circuits

OTA chips already configured as VCA are available, such as the SSM2024 quad current output VCA. This device is optimised for audio and musical instrument work and offers 82dB S/N at 0.3% THD. A 4kΩ pot wired to the power rails, with a 1µF capacitance shunting the wiper to ground (ideal for the VCA) will supply a virtually noise-free control voltage and can be as far away from the mixer amplifier as demanded without loss.

Multiplier mixer
The VCA behaves as a two-quadrant multiplier, the output being the product of the input and a positive control. When one wishes to multiply in all four quadrants, where the control has values of both polarities, one may also apply transconductance techniques.

Where precision is not a key factor, standard OTAs are ideal. Using a VCA circuit and making a resistor connected to one of the sig-

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Fig. 6. CA3080 non-linearity compared with sine function (actual measurements, scaled) using the circuit shown in Fig. 5.

Fig. 7a (left) Basic voltage controlled amplifier and the addition of linearsizing resistors (7b, right)

Fig. 8. Heterodyne ultrasonic receiver. A1 and A2 form a highpass amplifier/filter while A3 and A4 act as the local oscillator. OTA A5 provides the mixing function. Used for bats.

An unusual use of this function is in a bat detector. Fig. 8: Bats employ a sonar system to avoid obstacles and locate prey, a system as much as $10^{12}$ times more efficient than sonar contrived by humans.

A standard ultrasonic transducer (32kHz in the prototype) will pick up bat squeak’s (usually around 16kHz to 150kHz), which are amplified by A1. A highpass filter with cutoff around 20kHz then removes audible noise (A2). Wien bridge oscillator A3, A4 produces a sine wave with a range of around 20kHz to 120kHz. This reference modules the bat signal in the OTA (A5). Op-amp A6 converts the current output of the OTA back to a voltage. The signal now contains not only the two frequencies fed into the CA3080 but also components at their sum and difference. The sounds from the bat, the signal from the reference oscillator and their sum should all be well above the 10kHz low filter, A7, leaving only the difference signal. The prototype had two PP3s as power supply, and included a
TBA620 amplifier, although a high impedance earphone would suffice. The correct functioning of the prototype loudly demonstrated itself by ultrasonic emissions from a nearby video monitor. If this configuration looks familiar to radio enthusiasts, it is because the circuit is effectively a direct conversion receiver.

There is a great deal of potential for any device that can represent signals out of the range of human senses (and that of typical measuring equipment) to an accessible form. For instance, plants make ultrasonic gurgling noises when they begin to run out of water. American researchers have even designed control equipment for timber drying kilns that changes the drying temperature according to ultrasound generated by microfracture in the wood structure.

Filters
In many circuits it is possible to replace existing components with OTA circuitry and thereby introduce voltage control of otherwise fixed parameters. A simple application of this is to replace the R of an RC lowpass filter with an OTA, as in Fig. 9. Grounding the input of this circuit, and feeding the signal through a capacitor to point X (omitting the existing capacitor) produces a voltage controlled version of the RC highpass filter. Like their passive counterparts, one may cascade stages to increase the order of the filter.

The circuit of Fig. 10 was designed to find the best frequency for a loudspeaker crossover for given speakers. A voltage controlled filter with a 2nd order Butterworth response is constructed around the OTA. The lowpass output is then subtracted from the input signal to give a highpass output. The crossover frequency of the complementary outputs can be moved over the range of around 250Hz to 2500Hz. In this circuit, as in the other filter circuits featured here, one can change the frequency range by scaling capacitors.

Active differentiators and integrators may be easily constructed with OTAs, with the advantage that their time constant is voltage controlled. The versatility of the standard dual-integrator state variable filter increases with the addition of voltage control, as in Fig. 11. The Q may be adjusted by changing $R_R$ (adding another OTA here would give voltage control of Q). With the values shown, the centre frequency range is roughly 150Hz to 7.5kHz. Coupled to a sweep generator, this would allow plotting of system output against frequency. With the circuit tracking a swept sine wave, distortion against frequency could be plotted from the notch output.

By adding frequency dependent components to the feedback path of the simulated resistance in Fig. 9, reactance may be synthesized, the reactance appearing between X and ground. A circuit with more interesting possibilities is shown in Fig. 12. If a reactance is placed at the input port, its reciprocal appears at the output port. This gyrator-type circuit gives a simulated reactance that is fully floating – as long as the differential voltage does not exceed the voltage range of the LM13700 and has a value dependant on the control voltage.

VCO
Minor structural changes to the OTA state variable filter produce a good quality voltage controlled oscillator. The circuit of Fig. 13 generates a sine wave with a frequency range between 100Hz and 1250Hz. Although this circuit has a range considerably narrower than the circuit given in National Semiconductor.
data, it uses one LM13700 rather than two. If an op-amp buffers the output, and the preset
adjusted to give 4V p-p output, the distortion
is in the region of 0.01% at 1kHz, an order of
magnitude better than the NS circuit.

With a little experimentation it is possible to
build voltage controlled versions of many
standard op-amp circuits. For example, the
standard triangle/square wave oscillator
becomes voltage controlled by little more than
substitution of OTAs for op-amps and tweaking
of circuit values. Similarly, an op-amp
Schmitt trigger transforms to an OTA Schmitt
with voltage control of hysteresis.

One final word. OTAs have a frustrating
vulnerability to current overload on their con-
trol pins. Connecting the control of a CA3060
to ground without a limiting resistor will
instantly destroy the chip. You have been
warned.

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Fig. 12. Gyration-type circuit transforms resistance

Fig. 13. Low distortion voltage controlled oscillator

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