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[1], 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_{set}, I_{bias} or I_{abc}) 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_o=g_mxR_{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_3, 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 LM13700, **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-

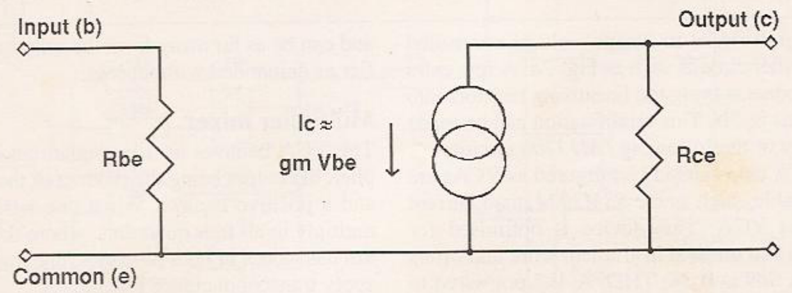

Fig. 1. Transconductance model of a transistor

cuit 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 converter2.

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 g_m control pin selects one of several inputs. The *CA3080* has an extra benefit here: its standby power demand is only 10µW.

The 50V/µs 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. 7a**. A few extra components bring the linearising resistors into play as in **7b**. This modification can be made to any of the following *LM13700* circuits

OTA chips already configured as VCAs 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 4k7 pot wired to the power rails, with a 1µF capacitor shunting the wiper to ground (local to 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[3].

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-

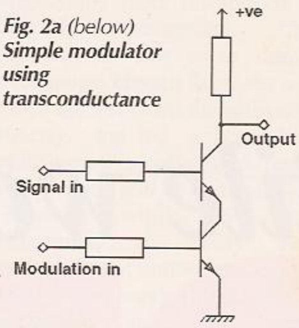

Fig. 2a (below) Simple modulator using transconductance

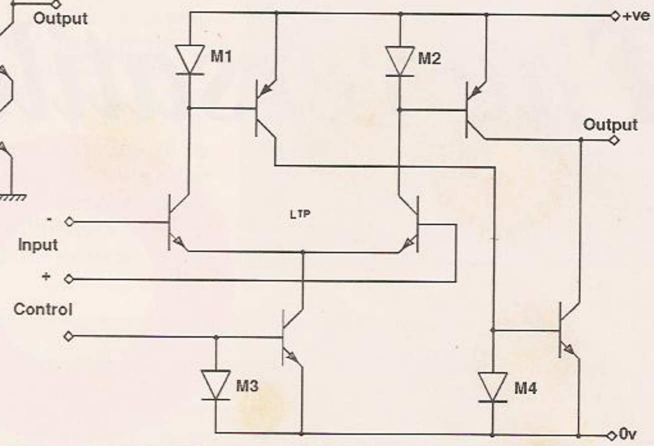

Fig. 2b. Basic operational transconductance amplifier

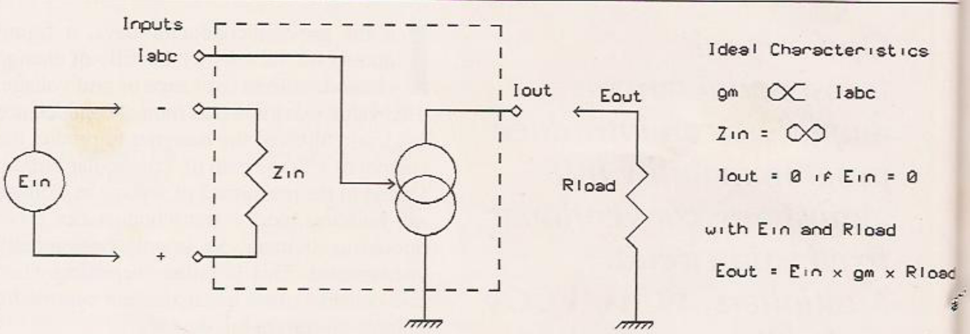

Fig. 3. Functional diagram of an OTA

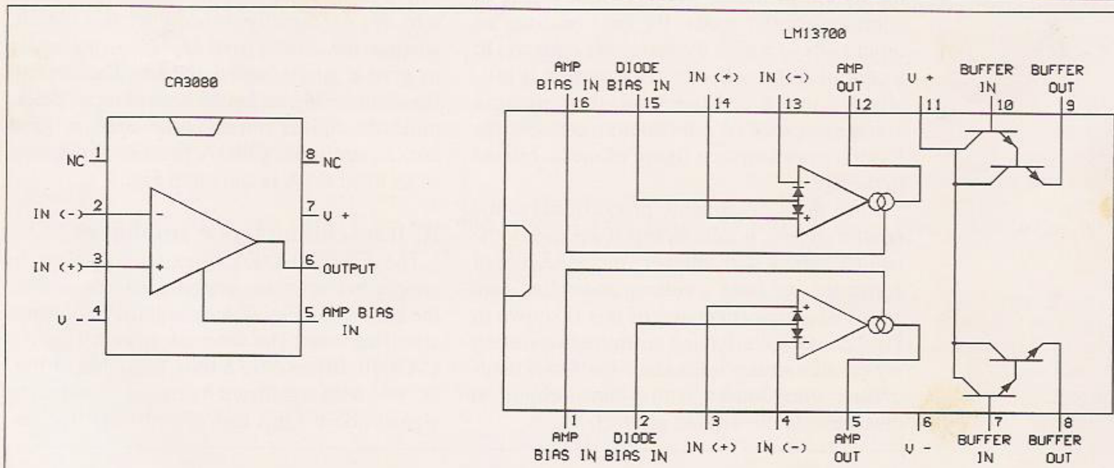

Fig. 4. Devices such as the LM13700 have significantly better specifications. The internal circuitry of the CA3080 differs only a little from that of Fig. 2b, and adds significant harmonic distortion to signals above a few tens of millivolts.

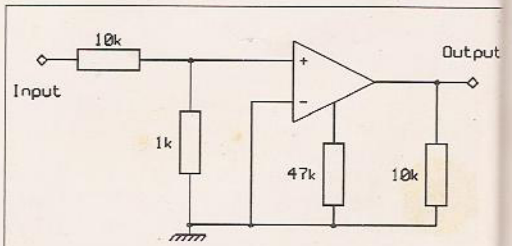

Fig. 5. Circuit to demonstrate nonlinearity of CA3080

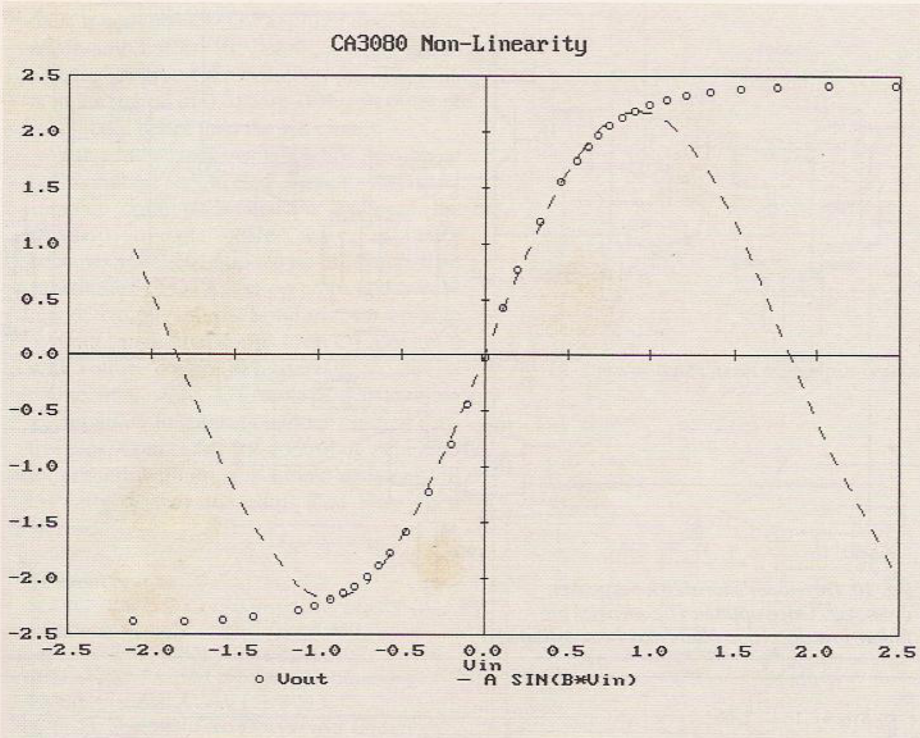

Fig. 6. CA3080 nonlinearity compared with sine function (actual measurements, scaled) using the circuit shown in Fig. 5.

nal source act as part of the OTA load, the input and control will be multiplied at the output. Several analogue music synthesizers featured modified VCAs with circuitry to cancel out two-quadrant products as ring modulators. Even when the *CA3080* is wired as a VCA, this chip has four-quadrant multiplication products at its output because of its nonlinearity.

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[4].

A standard ultrasonic transducer (32kHz in the prototype) will pick up bat squeaks (usually around 16kHz to 150kHz), which are amplified by A_1. A highpass filter with cutoff around 20kHz then removes audible noise (A_2). Wein bridge oscillator A_3, A_4 produces a sine wave with a range of around 20kHz to 120kHz. This reference modulates the bat signal in the OTA (A_5). Op-amp A_6 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, A_7, leaving only the difference signal. The prototype had two PP3s as power supply, and included a

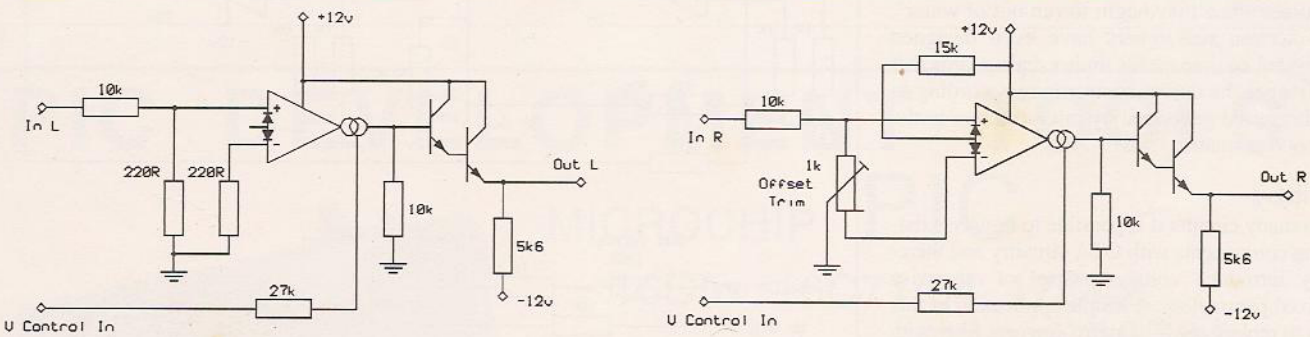

Fig. 7a (left) Basic voltage controlled amplifier and the addition of linearising resistors (7b, right)

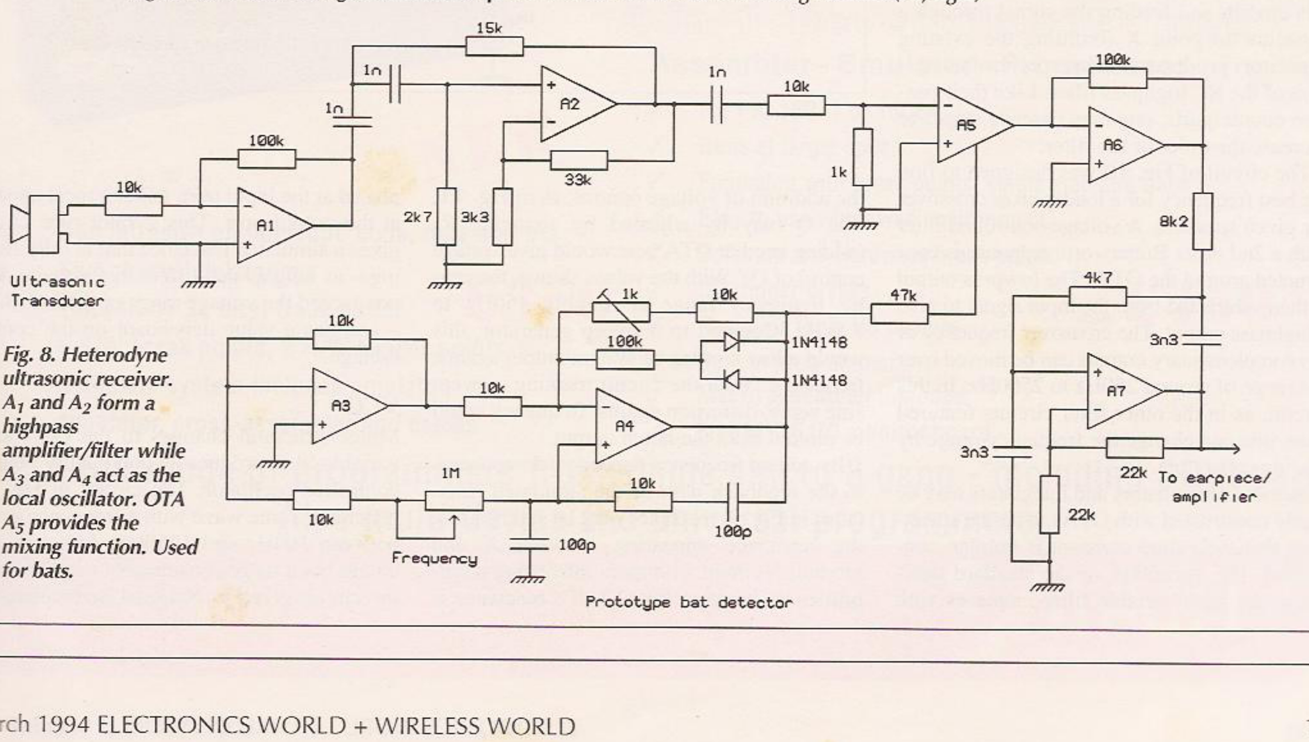

Fig. 8. Heterodyne ultrasonic receiver. A_1 and A_2 form a highpass amplifier/filter while A_3 and A_4 act as the local oscillator. OTA A_5 provides the mixing function. Used for bats.

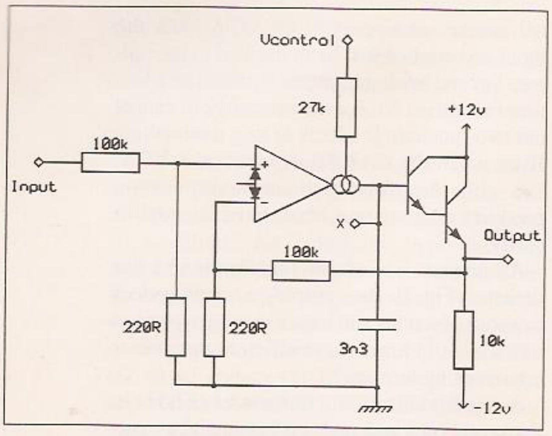

Fig. 9. Low pass filter using voltage controlled resistance. Grounding the input and feeding the signal through a capacitor to point X produces a tunable highpass filter.

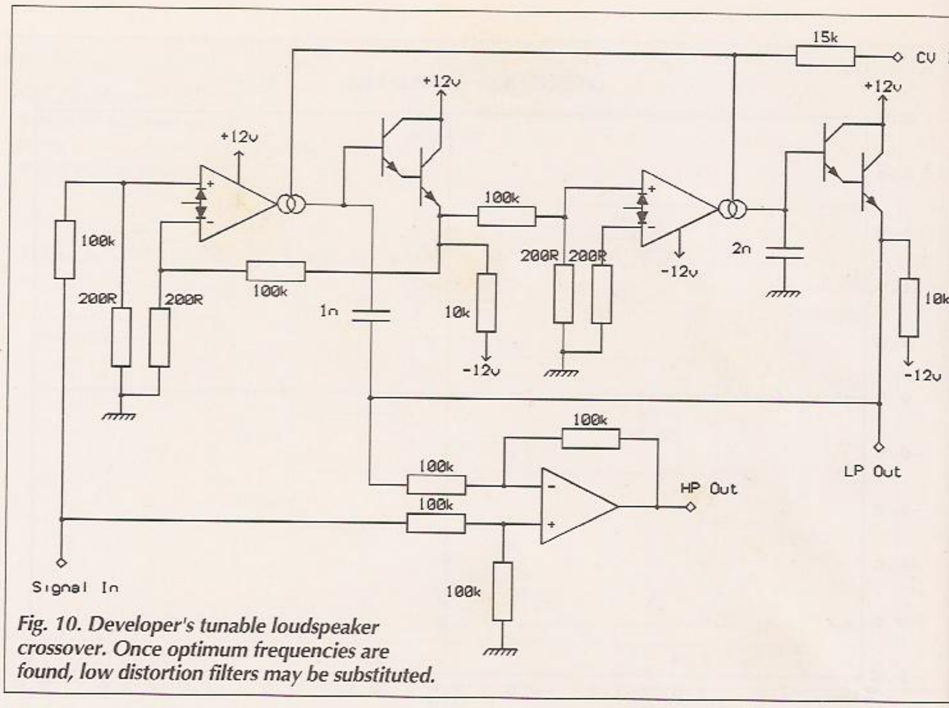

Fig. 10. Developer's tunable loudspeaker crossover. Once optimum frequencies are found, low distortion filters may be substituted.

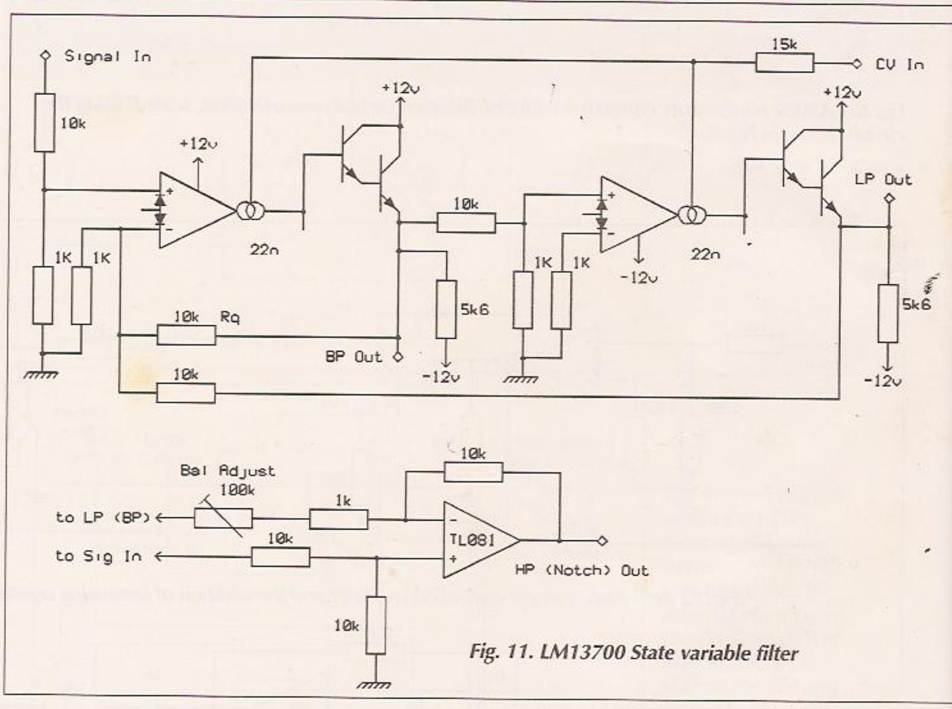

Fig. 11. LM13700 State variable filter

TBA820 amplifier, although a high impedance earpiece 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[5]. 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 by adjusted by changing R_q (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 control pins. Connecting the control of a *CA3080* to ground without a limiting resistor will instantly destroy the chip. You have been warned. ■

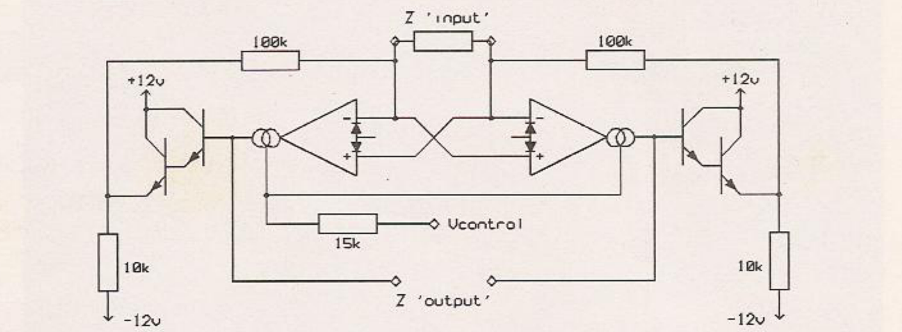

Fig. 12. Gyrator-type circuit transforms reactance

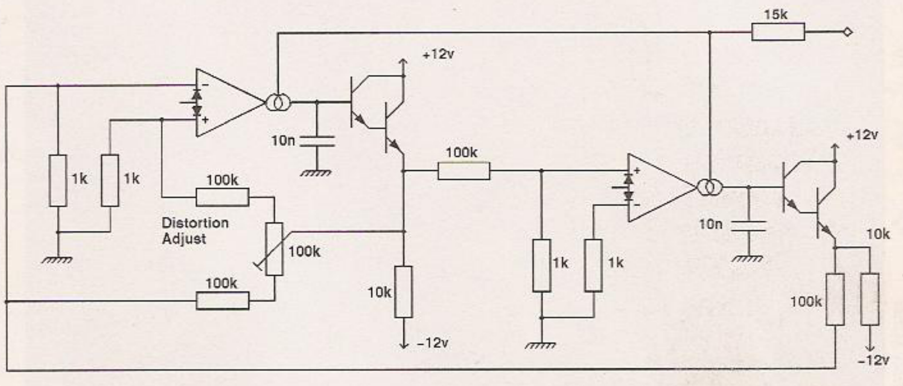

Fig. 13. Low distortion voltage controlled oscillator

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