

Sept 13, 2013

THE “JUNG TRICK” APPLIED TO A DUAL OTA

INTRODUCTION

The Operational Transconductance Amplifier (OTA) [1] is quite probably the most important component used in analog synthesizers. We love ordinary op-amps, and would struggle to get along without them, but the fact that the OTA is inherently a multiplier makes it essential. The OTA is NOT an op-amp. In particular, while it has a differential input, its output is a current (not a voltage) and this current is proportional to the differential input voltage (bipolar) multiplied by a control current (unipolar) and it is thus a two-quadrant multiplier. For many years, the CA3080 (or LM3080, etc.) were the typical parts.

Improvements were made to the CA3080 (principally linearizing input diodes for a “Gilbert input” feature), on-chip buffers, and two OTAs on a 16-pin chip. Today, the LM13700 (or LM13600) is likely the most common. It is a commentary on the highly successful traditional OTA applications that many times we first asked how we could make the dual op-amps substitute for the CA3080 as a sort of “design default” (initially thinking of using just half the chip). Today the 3080 is hard to obtain and expensive (we had them at about 75 cents at a time an LF351 op-amp was about 30 cents – I saw one CA3080 offered for \$13 the other day). You more or less always have to consider how you can make an available OTA such as the LM13700 work in place of a CA3080.

One thing that seems to be generally true is that you can always use just 1/2 of a dual chip, ignore the linearizing diodes and the buffers, and wire the six pins you do need exactly like a 3080. It does seem that you could expect to use both halves if you needed two OTA's in a circuit, so at worst, you would have an unused odd half chip.

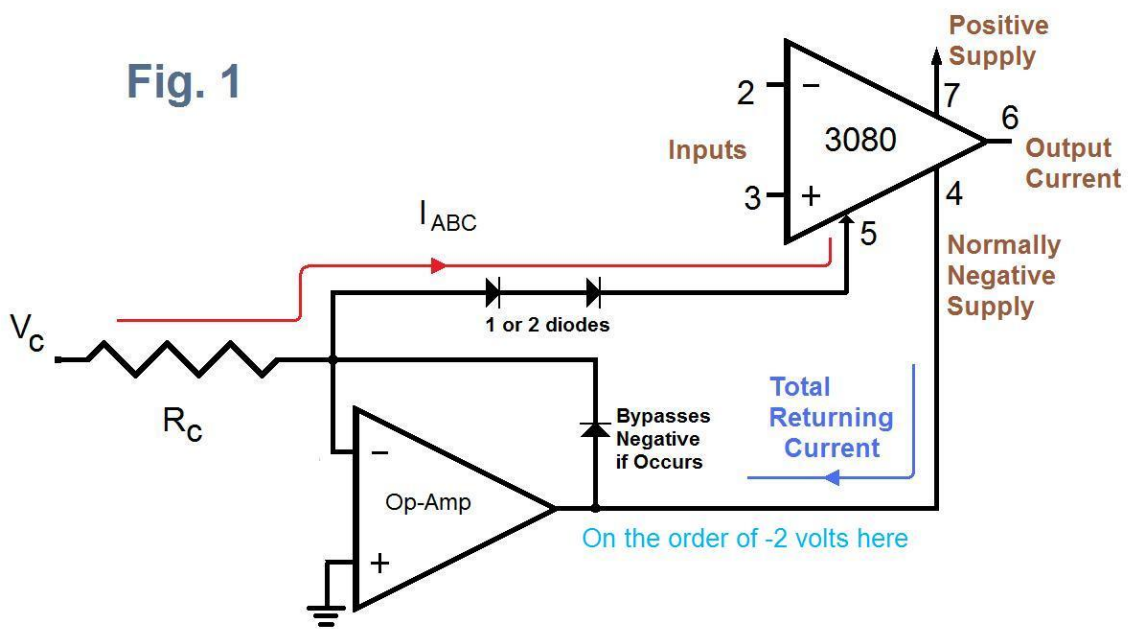
One exception would be the ingenious linear control scheme due to Walter Jung and published in JAES in 1975 [2]. This widely-admired “outside the box” scheme some of us call the “Jung Trick” has appeared in *Electronotes* publications many times [3-5]. The special consideration here is that instead of using the negative supply pin connected to a negative rail, it is connected to the output of an op-amp which collects up exactly the right current. The first time I saw this (as an AES show preprint), it threw me off. But this was only because I (and many others in subsequent years) were limiting ourselves to data sheets and suggested applications, while Walt was thinking of the OTA as a collection of current mirrors, and as a current handling device. Literally looking “inside the box” for an “outside the box” design.

So – how could we use Jung’s marvelous idea with a dual OTA? What do we know? Well I have always assumed you could use just half the chip just like a 3080. Recently Ian Fritz told me that he had in fact tried this and that it worked. It also seemed clear to me (and still does!) that if you connected the (-) supply pin to the output of an op-amp, you of course could not then connect the (-) supply to an actual negative supply. So you could not use the “Jung Trick” on half the chip, and then use a conventional (bipolar supply) for the second half. But could you use the Jung Trick on both halves. No, not exactly, as this would involve driving the (-) supply pin from two connected op-amp outputs.

This note suggests that you can, however, use series connected resistors to collect the currents with two op-amps. For example, you can form a pair of VCAs or a voltage-controlled cross fader. Things like that.

THE JUNG TRICK

The CA3080 produces an output current that is proportional to a differential input voltage on the (+) and (-) inputs, as multiplied by a controlling current traditionally called I_{ABC} (Amplifier Bias Current). In many (most?) applications we desire I_{ABC} to run from 0 (off) up to some maximum. A number of current sourcing Voltage-to-Current networks (often using op-amps, transistors, etc.) are possible. The simplest is a resistor (R_C) to an op-amp virtual ground. In order to have a virtual ground, you need feedback. Fig. 1 shows how Jung achieved the feedback through the negative supply pin of the CA3080. Note that I_{ABC} (V_C/R_C), the red current, flows into pin 5 of the 3080. The blue return current includes I_{ABC} but also other currents originating at the positive supply pin. Here pin 4, the normal negative supply pin, is at something like -2 volts.



SOME OLDER FIGURES

Fig. 2

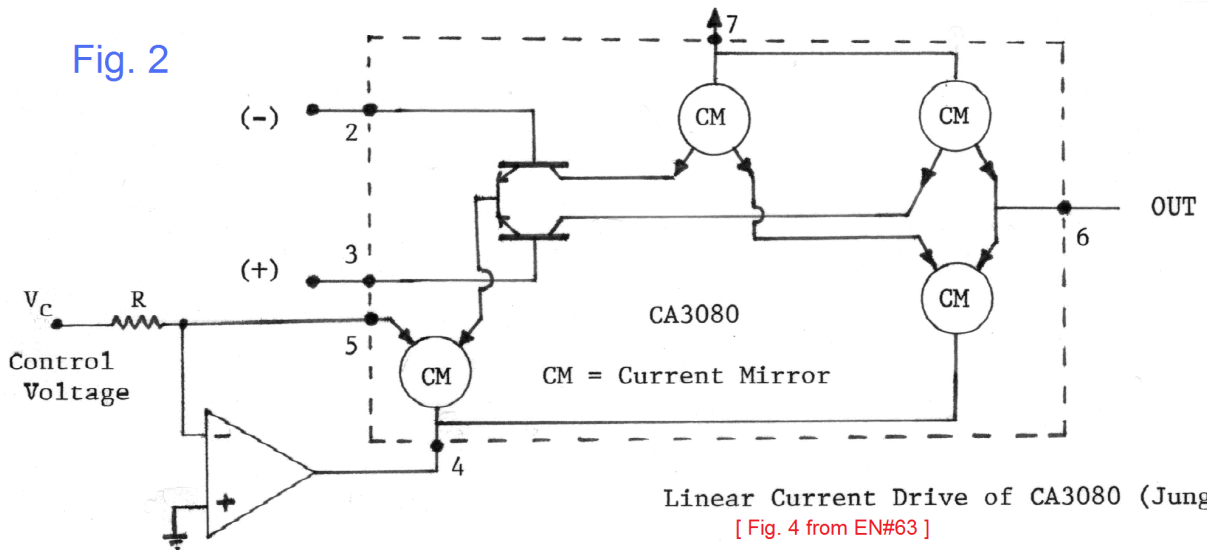


Fig. 3

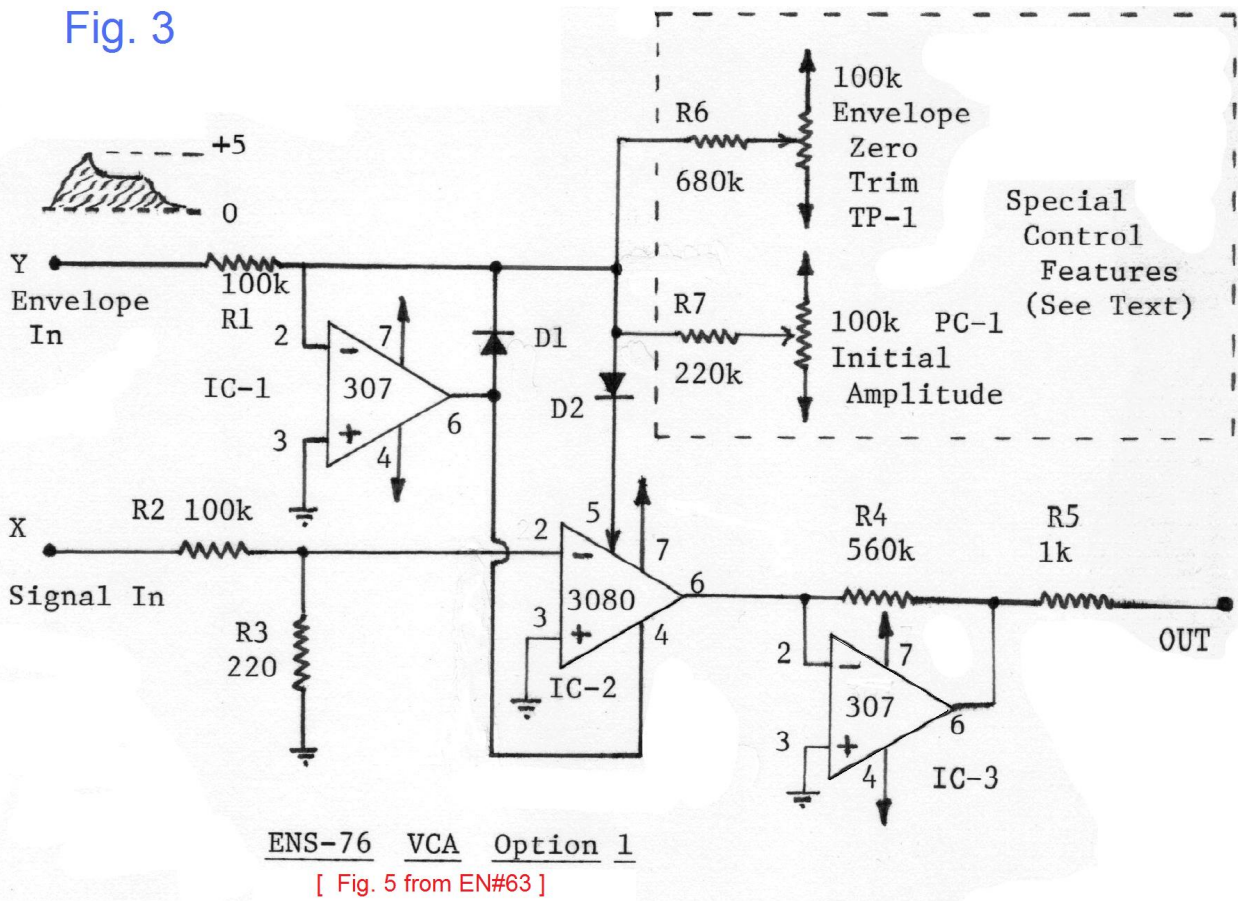


Fig. 2 and Fig. 3 are from EN#63 [3] and are reprinted here for easy reference. Fig. 2 shows us explicitly the current mirror structure of the OTA. The OTA is very different from an ordinary op-amp. Normally the diode-like structures of the current mirror at pin 5 sets the voltage at pin 5 about 1.2 volts more positive than pin 4. Thus when we connect pin 4 to negative supply (-15 say), pin 5 will take on a voltage of -13.8, if driven by a current source or just a resistor. [But if you use a resistor, keep it 33k or larger, or you can blow the OTA]. If we just used a resistor to pin 5 as the control current, zero would correspond a voltage of -13.8 volts (not that well defined). The Jung Trick is a way to make zero current correspond to zero volts, and be well defined. This is achieved by the feedback loop collecting current through pin 4 of the CA3080; the (-) input of the op-amp becoming a virtual ground, as noted earlier. So the purpose of any series diodes in the path leading to pin 5 is to lower the supply pin by about 0.6 volts for each one in the series. This allows larger input ranges for the OTA inputs (which are usually bipolar) and the output current may drive into bipolar voltages. Often we just output the OTA to another virtual ground (as in Fig. 3). Jung used one diode in his original circuits. Many of our Electronotes circuits have used two [4,5] although a good case for this is likely not at hand. Fig. 3 shows the ENS-76 VCA, a full implementation of the Jung Trick to a complete circuit.

THE NEW DUAL OTA TRICK

Let me confess right here that I do not fully understand the circuit that follows. It does seem to work just fine. In thinking about how to use the Jung Trick with both halves of a dual OTA (the LM13600 which I had, and probably the LM13700) I thought of using two op-amps to supply separate currents (pin 1 and pin 16) and collect up the currents at the negative supply pin (pin 6), as in Fig. 4.

It is bad practice to try to make two op-amps “agree” by connecting their output together. On the other hand, we know that an op-amp will drive into 1000 ohms that runs to any other reasonable voltage. Indeed, by using a standard 1000 ohm output impedance, we have made it possible to equally mix two synthesizer voltages by connecting them to a multiple. So, clearly I could run a 1k resistor to each of the op-amps, connect these resistors together, and run that to the supply pin (6) or the LM13700. At worst, something annoying would happen to prevent this from working to do what I had hoped.

But it worked – well – after fighting with it a bit (as usual).

What I had in addition to Fig. 4 was a ± 5 sinewave applied to pin 3 through a 10k to 20 ohm attenuator, with pin 4 grounded. Pin 5, the output current ran to a virtual ground op-amp with 750k in the feedback. The control voltage ran from 0 to +5. The output amplitude ran from 0 to 5. The second half of the dual OTA was similarly configured except there was a different sinewave frequency. I initially saw no strong interaction of the two signals. What’s not to like?

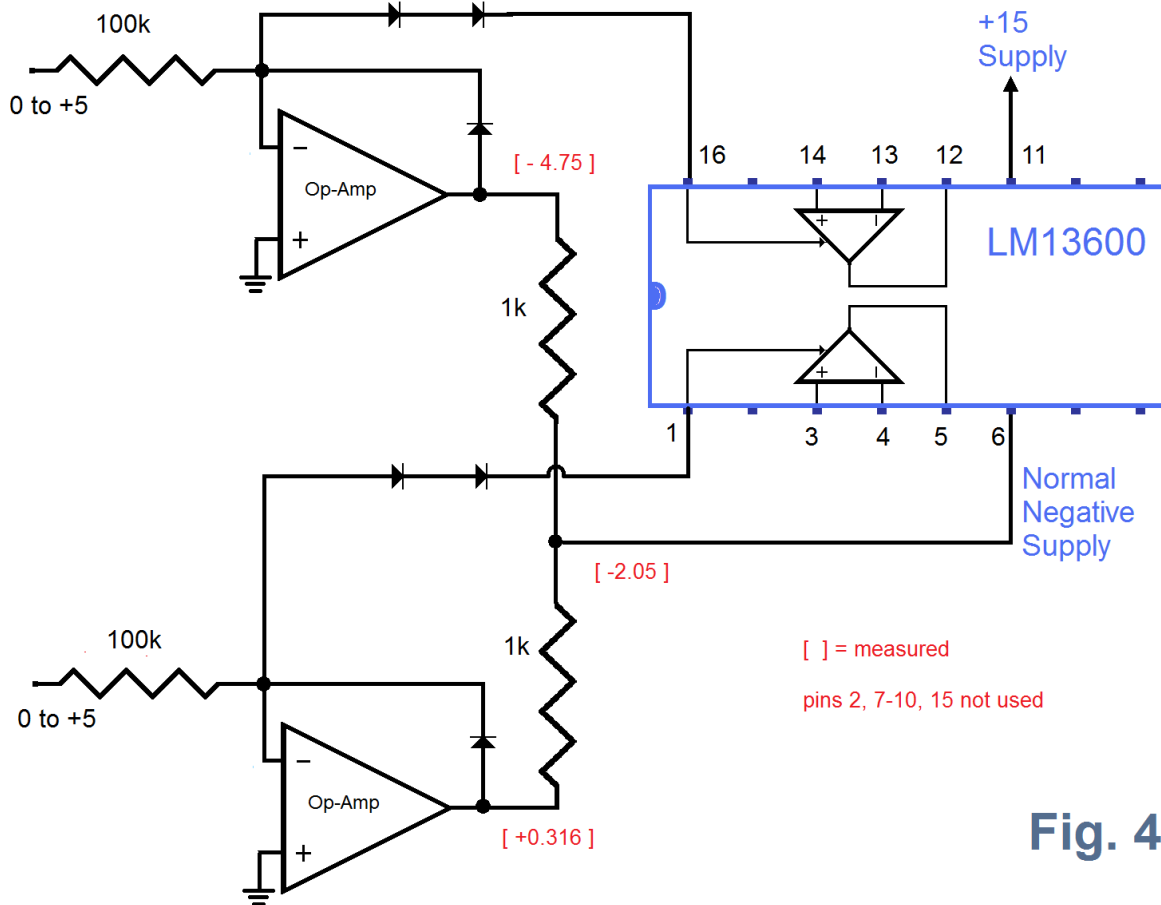


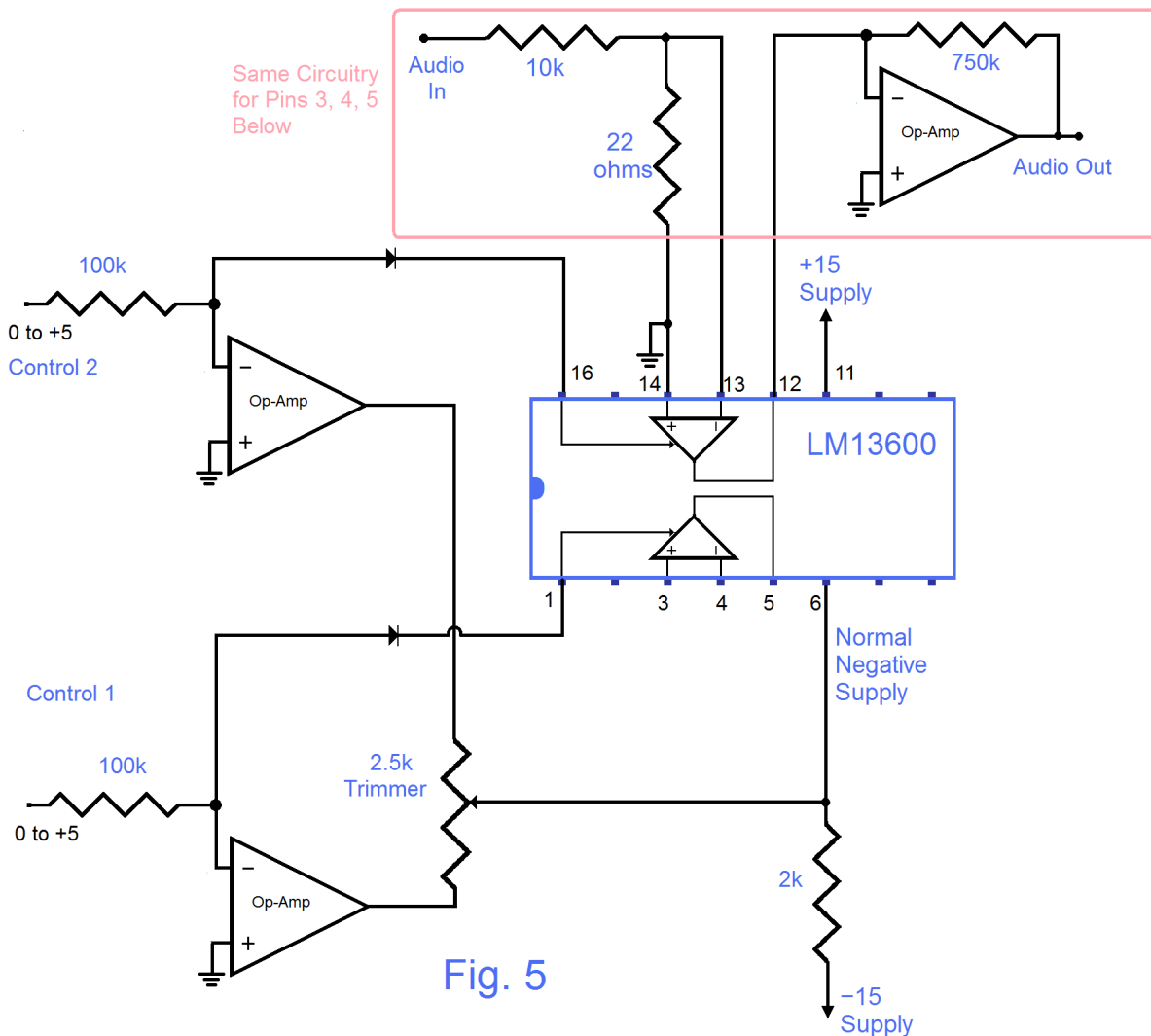
Fig. 4

Well, of course I was curious about the outputs of the two controlling op-amps. So I measured the DC level of the first one, and it was 0.316 volts. What! I was expecting something like -2 volts. I quickly tried the other op-amp. It was -4.75 volts. The junction was -2.05 volts. It thus seemed reasonable enough. The OTA chip was seeing the approximately -2 volts it needed to have. The two op-amps just had to work together to come up with a solution. For example, -6 and +2 would have worked. Also one might pin at -14 and the other would be +10. And – why not simply -2 and -2? There were an infinite number of possible solutions. So one is forced to either stop worrying about it, or ask the question: **WHY THIS SOLUTION?**

One naturally tries juggling/changing parts to see what makes a change in the outputs of the two op-amps. I did not do this exhaustively by any means. Changing the dual OTA, or the op-amps, or the 1k resistors does not seem to matter. Changing the diodes does seem to change the op-amp outputs, although they of course remain “balanced” so that the junction of the two 1k resistors remains fixed at about -2.

But the circuit still had tricks to play. So perhaps consider this a work in progress.

A more complete overall test, (influenced in large part by substituting components to find out what made a difference in the levels at the outputs of the controlling op-amps), showed that sometimes the two channels showed some interactions. In particular, when one control was all the way to zero, the other channel could go off as well. For another, when both channels were up, one channel could show just a trace of the signal from the other channel. (In this case, the “other” channel was perfectly clean.) Both these are serious problems. Thinking that the problem might be due to the fact that the two LM13600 OTAs were on the same chip, I decided to try the same circuitry with two separate CA3080s. The problems were much the same, although not identical. More or less playing around, strongly suspecting the kluge at the (-) supply pin was the gremlin, I arrived at what seems to be a fix. This is shown in Fig. 5, with the LM13600 put back.



Here we have taken out all but the one essential diode from each control path, but that is not likely part of the fix, nor is the explicitly shown audio paths shown in the upper portion around pins 12, 13, and 14 (or the audio signal inversion removed here). What is new is first we have added a third resistor of 2k running to the negative supply so that the junction between the two control op-amps has a third contribution. This cures the problem of the low control input shutting down both channels. (It seemed that this shut-down was due to the (-) supply pin jumping positive – this 2k resistor prevented that. There remained the second problem of the leakage, and this is the propose of replacing the two 1k resistors with a 2.5k trimmer (which I had available). It was possible to adjust this trimmer so that the leakage essentially disappeared. One needs to just adjust this until the signal in the misbehaving channel just starts to drop away completely, and then back off slightly. This done, the two VCAs are independent, both can be turned fully on, fully off, or any combination is possible without “cross-talk”.

These repairs to the design were based on intuition, and I do not understand what is going on completely. The two control op-amps have outputs of about +9 and -9, with the junction then pulled to about -1.2 volts by the 2k resistor (as makes sense). Yes - A work in progress. A strange double feedback situation I don't recall encountering before.

REFERENCES:

[1] Our Electronotes publications are crammed with OTA applications. Start with Chapter 3b of the Musical Engineer's Handbook (1975)

<http://electronotes.netfirms.com/MEHChapter3bOTA.PDF>

and/or the series of four App Notes from 1977

<http://electronotes.netfirms.com/AN21-AN24OTA.PDF>

There are also many commercial app notes and, and even Wikipedia which has an excellent OTA external link by Gene Zumchak.

[2] Walter Jung, “Application of the Two-Quadrant Transconductance Amplifier/Multiplier in Audio Signal Processing,” *J. Aud. Eng. Soc.*, Vol. 23, No. 3, April 1975. See also Walt's slightly earlier “Get Gain Control of 80 to 100 db” in *Electronic Design*, June 21, 1974 as well as his *IC Op-Amp Cookbook* (Sams 1974)

[3] B. Hutchins “The ENS-76 Home Built Synthesizer System – Part 1,” *Electronotes*, Vol. 8, No. 63, March 1976. (see Fig. 2 and Fig. 3 of this note)

[4] B. Hutchins, “A Voltage-Controlled Oscillator with Through-Zero Frequency Modulation Capability,” *Electronotes*, Vol 13, No. 129, Sept 1981 available at:

<http://electronotes.netfirms.com/EN129.pdf>

[5] B. Hutchins, “The ENS-76 Home-Built Synthesizer System – Part 7, VCO Options” (see Option 3), *Electronotes*, Vol. 9, No. 75, March 1977, pp 14-16. Circuit is also at: B. Hutchins, “What About: Self-Frequency Modulation” , *Electronotes*, Vol. 23, No. 217 Sept 2013. <http://electronotes.netfirms.com/EN217.pdf>