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APPLICATION NOTE NO. 427

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TWEAKING A VCO WITH MINIMAL EQUIPMENT

We often get questions about the analog circuits we used in our synthesizers, usually about substituting parts. Also typically we get specific questions that I just can't remember or, with some 9000 pages, can't pinpoint easily. Happily there are some questions where we can offer some useful comments. Here is one such example I believe. It involves the "tune-up" or a VCO for control scaling, and for high-end compensation. It is also a cheerful case in that it requires little in the way of special equipment. You just use your ear. Now if you, like me, have a less than admirable musical ear, all you need here is the ability to compare UNISON pitches. Most everyone can do this very well. Try it if you doubt your ability.

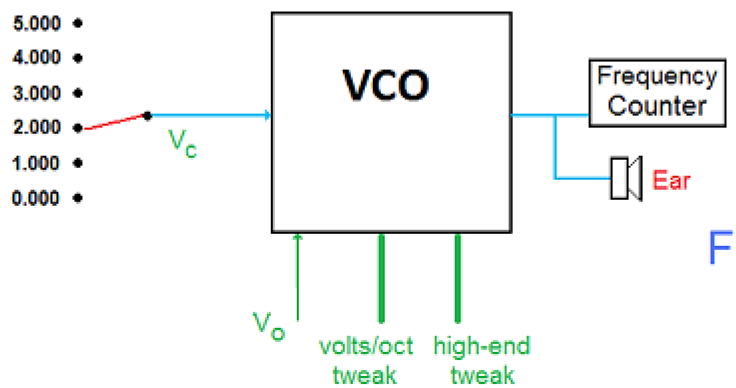

Fig. 1

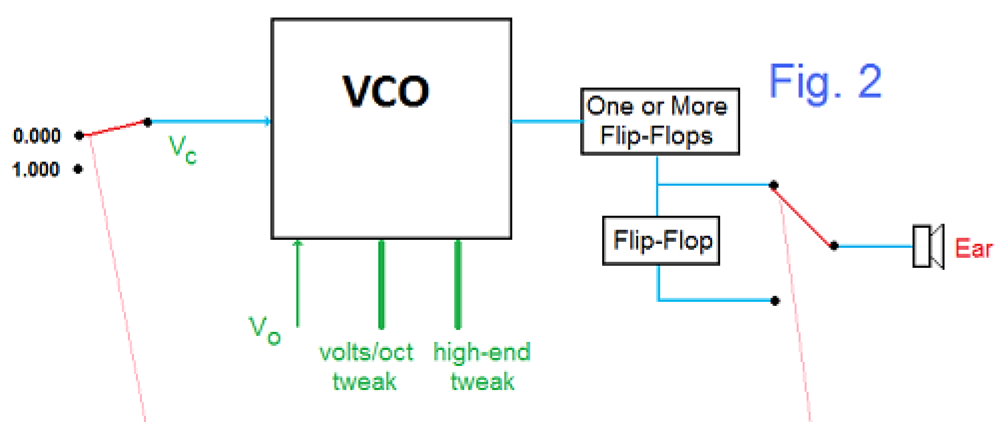

Fig. 2

So let's suppose you have just built a VCO and want to tune it to the specs of 1-volt-per-octave. At the same time you have in mind that it was desired as well to somehow tweak the high end so that it does not "droop" (go flat).

The bench setup of Fig. 1 seems appropriate. We have a switch to a series of integer voltages, good to 3 decimal places at least. This might be a pre-arranged reference bank, or perhaps a variable source with a good digital voltmeter. (It might even be a well-calibrated keyboard). We also show a reliable frequency counter.

It is straightforward to envision the tune-up procedure. If we had a good ear, we might just set an initial frequency with V_o, and then rotate the V_c switch and listen to hear if the lower octaves are sharp or flat. We kind of expect the upper octave or two may go flat. If your ears are not that good, we might rely on the frequency counter. In either case, we might achieve a good volts/octave tuning and then try to compensate the high end. Note that the volts/octave adjustment is just a well understood trim-pot (voltage divider) mechanism. The high end tweak on the other hand, may use any of a number of techniques. But this involves smaller adjustments, such as small resistors or small capacitors. These may well not be actual trim-pots, but only a soldering in of a slightly different fixed components. You may need to readjust the volts/octave following this high-end tweak, but probably not. You would perhaps see something like:

V_c	Un-tweaked High End	Tweaked High End
0.000	500	500
1.000	1000	999
2.000	2001	2000
3.000	3999	4001
4.000	7981	7998
5.000	15950	15997

These numbers are just made up. Keep in mind that while we expect these experimental data points are from a digital display, there are inaccuracies and "wobble" (as suggested by the numbers tabulated) such that you won't expect to repeat the results exactly again. If this looks like a lot of (uncertain) work, it is.

An alternative method is suggested in Fig. 2. This method is actually simpler and probably better in practice. Here we have only two switched reference voltages: 0 and 1.0000. (As we shall show later, we can tweak the high end even if this voltage is not precise.) Here we have added a number of flip-flops such as CMOS types 4013 (which come two to a chip). The flip-flops are triggered (perhaps requiring a level shift) from the VCO's square-wave output. Each flip-flop stage lowers the pitch one full octave exactly. We recommend at least one flip-flop to assure a perfect square wave of well-defined amplitude, and to lower the pitch to a range that is easier to hear. [Note that a frequency even as "low" as 2000 Hz seems "piercingly" high.] Once you have found a good division using the upper flip-flop group, add one more, switched as shown.

Now note what happens when the switch (a DPDT) is moved from the upper position (red as shown) to the lower. The 1.000 volts appears at V_c which nominally kicks the VCO up one octave while at the same time, the additional flip-flop at the other half of the switch lowers the output going to the ear by one octave. The pitch stays the same. In practice, it will change a tiny but detectable amount (for most people) and can volts/octave trimmer can be adjusted for an audible identity. This makes it easy to adjust this volts/octave.

Now, moving on to the high-end tweak. Assuming we have the lower ranges optimally adjusted, we have only to turn up V_o until we are in a higher range (changing the number of flip-flops in the upper chain if desired) and we repeat the procedure with the tweaking mechanism. Perhaps the upper octave is just a bit flat. We might simply add a few hundred ohms to tweaking series resistor. Likely a few successive approximations will get the response satisfactory. You are almost done – perhaps you are done.

Note that nothing involved on the high end depended on your having the lower octaves at exactly 1 volt/octave. For example, what if your supposed 1 volt source were actually 0.98 volts. It may be that you will need to readjust the volts/octave not just because your reference voltage was inexact, but ultimately to match to your keyboard which is likely also inexact. But this you would have had to do eventually anyway. The point is that the high end compensation is almost certainly still near perfect. [If it helps, consider that you have "souped up" the high-end switching, just as though you used a faster component, and it now works in that upper range.].

A few additional remarks.

(1) High-end tweaking usually has a theory and a practice. In practice, a theoretical component may need to be experimentally adjusted – perhaps 20%, perhaps 50%, or more. We are dealing with fine adjustments, and relatively <u>large</u> changes in <u>percentage</u> of small components are still small, and plenty of "second-order" effects are in play. [It's kind of like fixing the dip of a bridge by one prop at the end, even though we could have fixed this beam and that girder individually.]

(2) It is because there is <u>only one voltage in Fig. 2, used for all octaves</u>, that we expect and get better results. Fig. 1 requires that all 6 voltages have a consistent difference of 1 volt. The high end tweak might be under-done because the top voltage might be, 5.003 instead of 5.000, for example. [It's like the guaranteed linearity of one bit D/A and A/D converters in digital audio.]

(3) Note that high-end tweak in general distorts the waveshape! But we only needed to get the frequency right. WE do get harmonic distortion as a result, but by the time you get to 16 kHz, the first harmonic is already above audio.

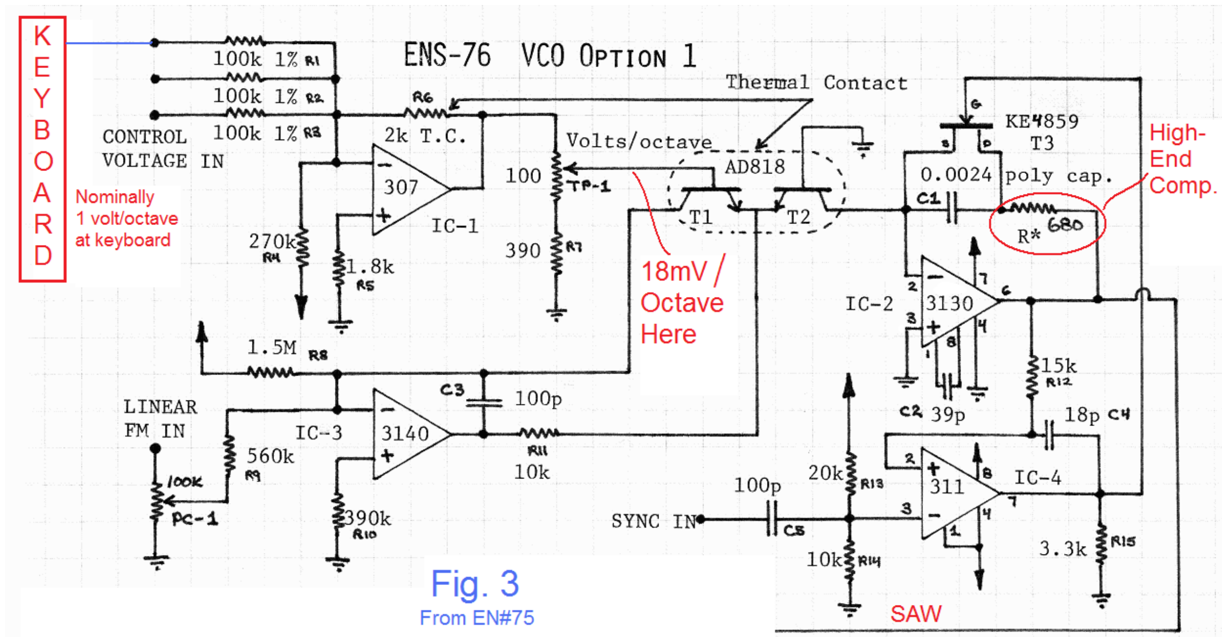

Fig. 3
From EN#75

(4) Fig. 3 shows a specific circuit from EN#75. This is shown here to make the main point that the VCO is only indirectly tweaked for 1 volt/octave. Moog originated the 1 volt/octave standard quite sensibly to use a larger voltage range for the keyboard output (avoiding noise). Yet this exponential VCO circuit (and most, probably all others) is based on the BJT equation relating collector current to base-emitter voltage as:

$$I_c = I_0 e^{V_{BE}/26\,(millivolts)}$$

See ***Musical Engineer's Handbook***, etc. if this is unfamiliar. In order to raise the frequency by one octave (double the collector current) V_{BE} needs to change by:

$$V_{BE} = 26mv \ln(2) = 18\,mv$$

Thus the actual control voltage is 18 mV/octave. This is why the input summer has a gain of 0.02 (2k/100k) and is followed by a trimmer (TP-1) as part of a voltage divider to further tweak it down to about 0.018. You knew this.

Now, suppose you tweaked the VCO to 1 volt/octave as in Fig. 2. But, suppose further that your keyboard is a bit low (perhaps it has a current in a divider string that is only 98% what was intended. Despite your careful tuning, the synthesizer is flat.

It was our practice to (simply) show the control inputs for all our VCOs as three parallel 100k resistors, while the accompanying text indicated that (the input stage being a summer) we could have additional inputs, variable inputs, coarse and fine manual tuning, etc. You would however almost certainly have one input dedicated to the keyboard (a direct 100k waiting for a plug bringing the keyboard voltage - blue in Fig. 3). This is probably the only input to tweak to. So if you find the VCO going flat with your actual keyboard, you could re-tweak the volts/octave as a fix. I guess that even if you fixed the keyboard, or if it was already near nominal, you probably couldn't resist the temptation to optimize the whole thing.

Note well, as suggested above, you do NOT need to re-tweak the high-end comp. Incidentally, for this circuit, the high-end tweak is the 680 ohm series resistor, as an example. What it does is add a tiny amount to the ramp voltage causing the ramp reset to fire just a tiny bit early (a time proportional to current, which is quite small in the low-frequency range).