ELECTRONOTES 75

Newsletter of the Musical Engineering Group
203 Snyder Hill Road
Ithaca, N. Y. 14850

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GROUP ANNOUNCEMENTS:

CONTENTS OF EN#75

In this issue, we have prepared the presentation of the VCO's for the ENS-76 system. This completes the basic foundation of the system. We do expect to go on with the system with new additions for most of the rest of this volume, so there is much more to come. The present series of VCO's should give a good variety of features to the builder, many of which have not been presented in an ENS series before.

NEW MEMBERS AND ADDRESS CHANGES (c):

Ernst Bonis	Reggestraat 17, Dongen, Holland
Charles Boody	1512 E. Nall, Sherman, TX 75090 (c)
Martin Bosch	RR#2 Huntoon Rd., St. Joseph, MO 64505
Bruce R. Bouchard	17 Croissant de la Paix, Aylmer, QUE Canada J9H 3X7 (c)
Martin Brunet	Pasaje Oller 17, Manresa (Barcelona), Spain
Richard Bugg	2703 N.W. 20th, Oklahoma City, OK 73107
Allen H. Burdick	Drawer G, Ithaca, NY 14850
Gary Burma	2748 Dundas St., Vancouver, BC Canada V5K 1R2
Dave Christie	96 Gerrard St. E Apt 7d5, Toronto, ONT Canada M5B 1G7 (c)
D. H. Cockerell	2 Rue des Halles, 75001 Paris, France
Juan Bermúdez Costa	c/ Navas de Tolosa 368- 4.1., Barcelona 13, Spain
Michael Coxe	24 Dixie Trail, Raleigh, NC 27607
Don Dammann	138-7 Nimitz Dr., W. Lafayette, IN 47907
James Dashow	Via della Luce 66, 00153 Roma, Italy
Wm. Doscher	698 Orchard, Sarnia, ONT Canada N7V 2X2 (c)
Trip Doss	116 Wiess College, PO Box 2011, Houston, TX 77001
K. S. Dulay	5 Llewellyn Rd., Leamington Spa CV31 2BJ, Warwickshire, England

James Dziedzic	8202 Deer Creek Lane East, Canton, MI 48187
Douglas Feld	11 Burbank House, Stanford, CA 94305 (c)
M.M.B. Araujo Filho	Rua General Glicerio 82 Apt 401, Laranjeiras ZC-01, Rio de Janeiro, RJ-20.000 Brazil
David Gatzen	Room 413 Batterson C, Univ. of Ct., Storrs, CT 06268
Felipe Gonzalez G.	Apartado Aereo #34, Car 9ª No 21-25, Pereira, Colombia
Robin Graham	Roland Corp., 2-26 Shinkitajima, 3 Chome, Suminoe-ku Osaka 559, Japan
Charles Haglan	635 N. Scott St Apt AA, New Orleans, LA 70119
Harvey E. Hahn	14 N. Highview, Addison, IL 60101 (c)
Graham Hinton	3 Kersland St., Glasgow G12 8BN, Scotland
Jim Hodges	Star Route 2, Box 15, Keyser, WV 26726
David Johnson	Mittlere Str. 55, CH 4056 Basel, Switzerland
Nicholas Kilbourn	67 Glen Rd., Toronto, ONT Canada M4W 2V5 (c)
Dave Lustig	2005 Fairburn Ave., Los Angeles, CA 90025 (c)
James Manley	301 Fairgrounds Dr C4, Vallejo, CA 94590 (c)
Paul A. Marosi	29023 Marquette, Garden City, MI 48135
John F. Melville	53 Lynn St., Peabody, MA 01960 (c)

News Items:

It should be no real surprise but a matter great pleasure to learn that Don Lancaster has written the book everyone was waiting for: The CMOS Cookbook. The book has been released by Howard W. Sams. The style and format follow closely that of the well known and much appreciated TTL Cookbook. Watch for this one and get a copy as soon as you can.

We have received the first issue of the Computer Music Journal. This seems to be an excellent addition to the literature, and is recommended to all our readers, and particularly to those working with synthesis by digital computer. This first issue contains papers by James Moorer, John Snell (who is also the editor), Dexter Morrill, and Steve Saunders, and seems to center around the computer work at Stanford Univ. and related material. The reader will also get numerous literature leads from the references listed. Subscriptions are $14 for one year and $26 for two years available from Computer Music Journal, PO Box E, Menlo Park, CA 94025

A "Festival of Microtonal Music" will be held at Webster College, St. Louis, MO from April 1 to April 7, 1977. The festival will consist of lectures and performances. For further information, contact Robert Chamberlin at Webster College, 470 East Lockwood, Webster Groves, MO 63119 (314)-968-0500 ext. 330 or 338.

The "Cat" is a small portable synthesizer produced by Octave Electronics Inc., 32-73 Steinway St., Long Island City, NY 11103. The unit features a 37 note keyboard, two VCO's with suboctave feature, ADSR and AR transient generators, sample-and-hold, noise generator, VCF, VCA, and LFO, along with a price of $599. Write to Octave for more information.

A new item from a new company is the "Synare P.S." (Percussion Synthesizer) from Star Instruments Inc., PO Box 71, Stafford Springs, CT 06076. The instrument is controlled by ordinary drumsticks which strike four rubber pads, and thus control over a number of synthesis processes is achieved. The unit has a number of standard synthesizer type modules in a prepatched panel. Write for more information and the location of a local dealer.

The New England Conservatory of Music will hold a Summer School from June 27 to August 5, 1977 and will include an Electronic Music Workshop, June 27 - July 1 with Robert Ceely, and Basic Audio and Recording Workshop for Music Educators, July 25 - July 29, with Robert Rachdorf. For more information, contact Bob Annis at (617)-262-1120. The N.E. Conservatory is located at 290 Huntington Ave., Boston, MA 02115.

THE ENS-76 HOME-BUILT SYNTHESIZER SYSTEM - PART 7, VCO OPTIONS:

-by Bernie Hutchins, ELECTRONOTES

INTRODUCTION

We have chosen for the ENS-76 system six different VCO options which we will number 1, 1a, 2, 3, 4, and 5. Each of these has a combination of features which we feel make it a useful option. However, many of the features of one design can easily be used in another of the circuits, so the builder should feel free to experiment around. In this introduction, we will be briefly describing the different options. We shall be giving the main design features in the options, and for the benefit of those readers who are familiar with our earlier VCO designs, will point out the ideas that are new. This will permit the experienced designer to briefly scan the designs for new features without going over the circuit descriptions in detail.

VCO OPTION 1: This VCO is pretty much a standard VCO, with the exception that it has a Linear FM input which has been added because it is useful and easy to implement The basic oscillator was given by Terry Mikulic in EN#62 (13). This option is intended to give the greatest accuracy and range of any of the designs. We used a somewhat simpler exponential stage here. The heart of the design is really the Analog Devices type AD818 NPN matched pair which has been optimized by the manufacturer for log conformance. A small amount of reset compensation (R*) has been added to the design, but basically, we rely on the matched pair to keep the high end up (see the full circuit description for more information). The circuit has ±10 volt signals throughout the waveshaping circuit, and it is trivial to bring out these signals, although we have chosen here to bring out our standard ±5 volt signals. We have used a "counter-glitch" correction in the saw-to-triangle converter (see the Utility VCO in EN#67), and because we have a ±10 volt triangle available, it is convenient to use the FET type triangle-to-sine converter.

VCO OPTION 1a: This VCO is identical to Option 1 except here we use the exponential converter used by Terry Mikulic in his original design. The advantage here is that the CA3046 transistor array costs under a dollar, while the AD818 pair in Option 1 runs five dollars in single units.

VCO OPTION 2: Option 2 is pretty much a "workhorse" VCO, but it does have one new feature (Symmetrized Ramp Modulation - SRM) and a number of new circuit tricks are given. For a discussion of the Symmetrized ramp, see the discussion by Bill Hartmann in EN#67. This circuit uses the triangle-square type of basic oscillator rather than the sawtooth oscillator in the designs above. In previous VCO's using the CA3080 as a current reversing switch, we have had to use an extra inverter or current mirror to properly drive the CA3080 and at the same time, have higher voltages correspond to higher frequencies. It is much simpler to just reverse the two base connections in the standard converter (we should have thought of using this earlier!). The basic oscillator is similar to those we have used before, but be sure to chalk up another trick to the CA3080's bag - it makes a good Schmitt trigger. We got this idea from the application notes on the type CA3140 op-amp (see RCA File No. 957). The waveshaping circuitry is standard, except we have used Bill Hartmann's triangle-to-saw method and implemented the symmetrized ramp modulation he suggests.

VCO OPTION 3: Option 3 uses a basic oscillator similar to that of Option 2, but here we have enhanced the capability for Dynamic Depth Linear Frequency Modulation (DDLFM). Note that this VCO has an input for an envelope generator! This envelope (or other control) is fed to an internal VCA which controls the depth of modulation. The VCO accepts external modulation, but will also accept self-modulation (harmonic spectrum). We have not put any waveshapers in this one. Instead, a single "spectral density" control changes the waveform through use of self-modulation.

VCO OPTION 4: In Option 4, we carry the linear modulation feature one step further to obtain both dynamic depth and through-zero modulation possibilities. See the work of Douglas Kraul in EN#62 for more information on this type of oscillator. Since this is really a special purpose oscillator, and because a wide variety of timbres are available through the use of self-modulation, we have not added any of the conventional waveshapers to the circuit.

VCO OPTION 5: Option 5 is another special type of VCO, and is used mainly by way of illustration. We are calling it a "low distortion sinewave VCO" but it might well be considered a precision sinewave waveshaper. Here we have added two series single-pole low-pass filters to the usual triangle-to-sine converter to reduce the harmonic content (which is on the order of 1-2% out of the converter) to a much lower value. Note that we could mirror other circuits off the main converter in a similar manner. For example, we could have two more tracking oscillators for a "chord producing" VCO.

GENERAL FEATURES OF ALL THE OPTIONS

All the VCO's have the standard exponential response of 1 volt/octave with control voltages fed in through 100k. The output levels are ±5 volts, although it is generally possible to convert to a ±10 volt system with little trouble. For the most part, signals are handled with the type 556 op-amp. In 5 volt systems, it is possible to use the 307 type op-amps if optimum high frequency performance is not required.

In order to simplify the schematic diagrams, we have not shown specific input stages but instead will be using as an input for control voltages the structure shown in Fig. 1. This could of course be used as is, but we have in mind that in nearly all cases the builder will use something with more features. In particular, COARSE and FINE frequency controls are common, and a variable input may also be desired. There should also be at least one input that is the direct-in 100k 1% type. A possible input stage is shown in Fig. 2.

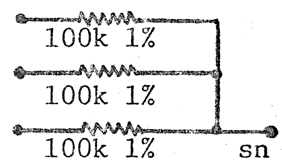


FIG. 1 INPUTS AS SHOWN

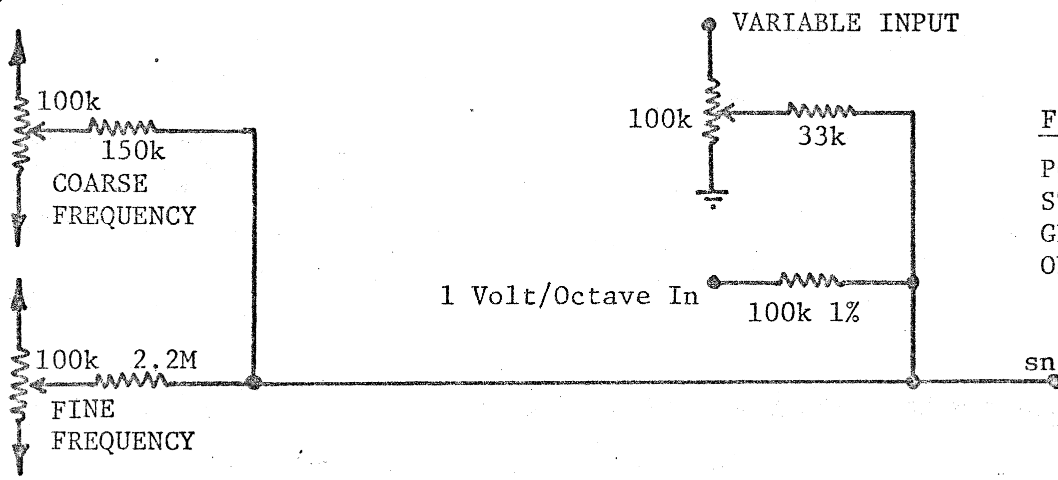
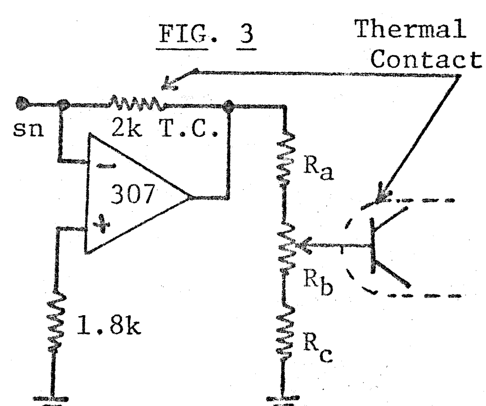


FIG. 2

POSSIBLE INPUT STAGE TO REPLACE GENERAL STRUCTURE OF FIG. 1

Beyond the summing node (sn) of the input structure, we will always find a scaling network which changes the 1 volt/octave at the input to the approximately 18 mV/octave that must appear at the base of a transistor. We also do a temperature correction at this point by means of the 2k T.C. resistor which is a Tel Labs type Q81k which has a positive T.C. of +3500 ppm/°C. This corrects for temperature variations in the transistors of the exponential converter. Thus, both this resistor and the transistors should be at the same temperature, and this is indicated by the "thermal contact" arrows. A typical input is shown in Fig. 3:

FIG. 3



In practice, thermal contact is made by mounting the resistor and the transistor pair or array so that they are touching, and then putting a small amount of heat-sink compound between them. For set-up purposes and testing, an ordinary 2k 5% resistor can be used. The T.C. resistor and heat sink compound can be put in during final packaging and calibration.

The resistors R_a, R_b (a trim pot, probably a multi-turn unit), and R_c are selected so that a one volt change at the input, through 100k, is scaled to an 18 mV change at the wiper of the trim pot. At the same time, it is best to maintain a low source impedance (say 1k or lower) so that the base of the converting transistor is held down well. Since the output of the op-amp will never exceed a voltage of much more than a few hundred mV, there is no problem with the op-amp driving such a low impedance. In the circuit diagrams, we will be showing the voltage divider shown in Fig. 4a (R_a = 0, R_b = 100, R_c = 390) which permits the voltage to be scaled from any values between 20 mV and 16 mV. This works quite well if a multi-turn pot is used, and gives a lot of excess room on the ends. A somewhat tighter divider is shown in Fig. 4b where R_a = 47, R_b = 100, and R_c = 820. This gives voltages scaled from 17 mV to 19 mV. If you are using the precision resistors indicated (the 100k 1% or better), this should work out well. If however you are just setting up with 5% resistors, you may need the extra room given by the circuit of Fig. 4a.

In any case, you will be adjusting the trim pot so that a 1 volt change at the input gives a one octave change of frequency. This should be set first at the lower frequencies (around 100 Hz) and then checked at higher frequencies, and compensated if necessary. Tuning is often best done by ear. As an aid, it is useful to have a precision one volt source which is switched in, and at the same time, a flip-flop is switched into the return line from the VCO. Thus, the pitch of the VCO should go up one octave, but the pitch returning should remain the same, because of the additional flip-flop. The original flip-flop is needed so that only square waves are compared. See Fig. 5 for this setup.

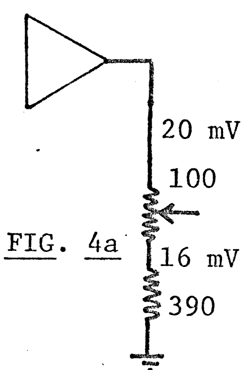


FIG. 4a

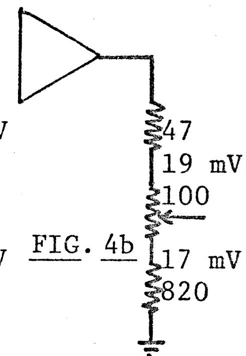


FIG. 4b

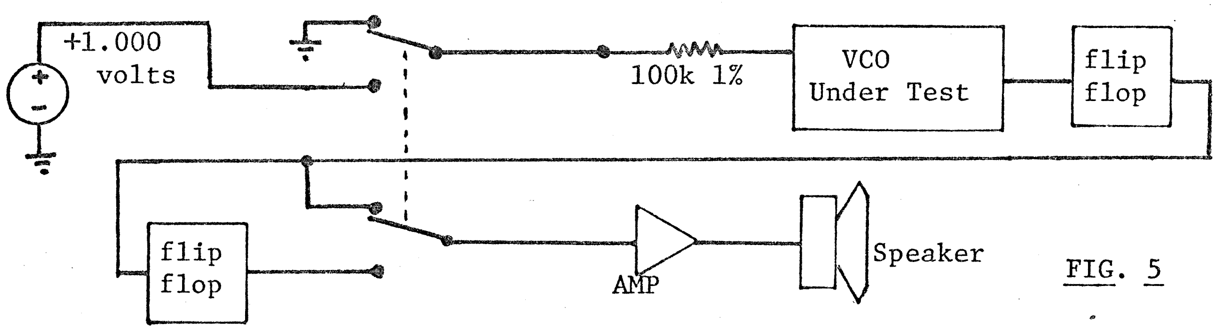


FIG. 5

Most of the other adjustments and calibrations that you will need to make are described in the circuit descriptions of the various options. Keep in mind that there are six different circuits, and we built each one only once. If you copy ours exactly, it should work, but you may have to do a little trimming to get everything exactly the way you want it. We were not overly careful to adjust the amplitudes to exactly the five volt levels, and made no trim adjustment provisions for amplitude except in one case. You should trim these up if you find it necessary. You can use a scope to do this if you have an accurate one. However, even if you don't have an accurate scope, you can use an accurate meter. You just set the VCO frequency to 1/10 Hz or below and read the peak of the meter. For making adjustments of waveshapers, it is best to use a scope, even if it is a relatively poor one. Note however, that when trimming up the sine wave, the best instrument you have is your ear.

ENS-76 VCO Option 1

The design goal for VCO Option 1 was to make a VCO with standard features that is as accurate and drift free as possible. The basic oscillator (IC-2 and IC-4) is a sawtooth generator based on the VCO described by Terry Mikulic in EN#62. This basic oscillator is driven by an exponential current source based upon the Analog Devices type AD818 matched NPN pair, which is probably the best exponential (log) transistor pair available. The output of the basic oscillator is a zero to +5 volt ramp (output pin 6 of IC-2). The rest of the circuit consists of waveshapers that are more or less standard, and provide Saw, Triangle, Square, Pulse, and Sine outputs, all with ±5 volt levels. It is easy to convert this one to ±10 volt levels if this is desired. The circuit also has inputs for Linear Frequency Modulation, and for standard Pulse Width Modulation.

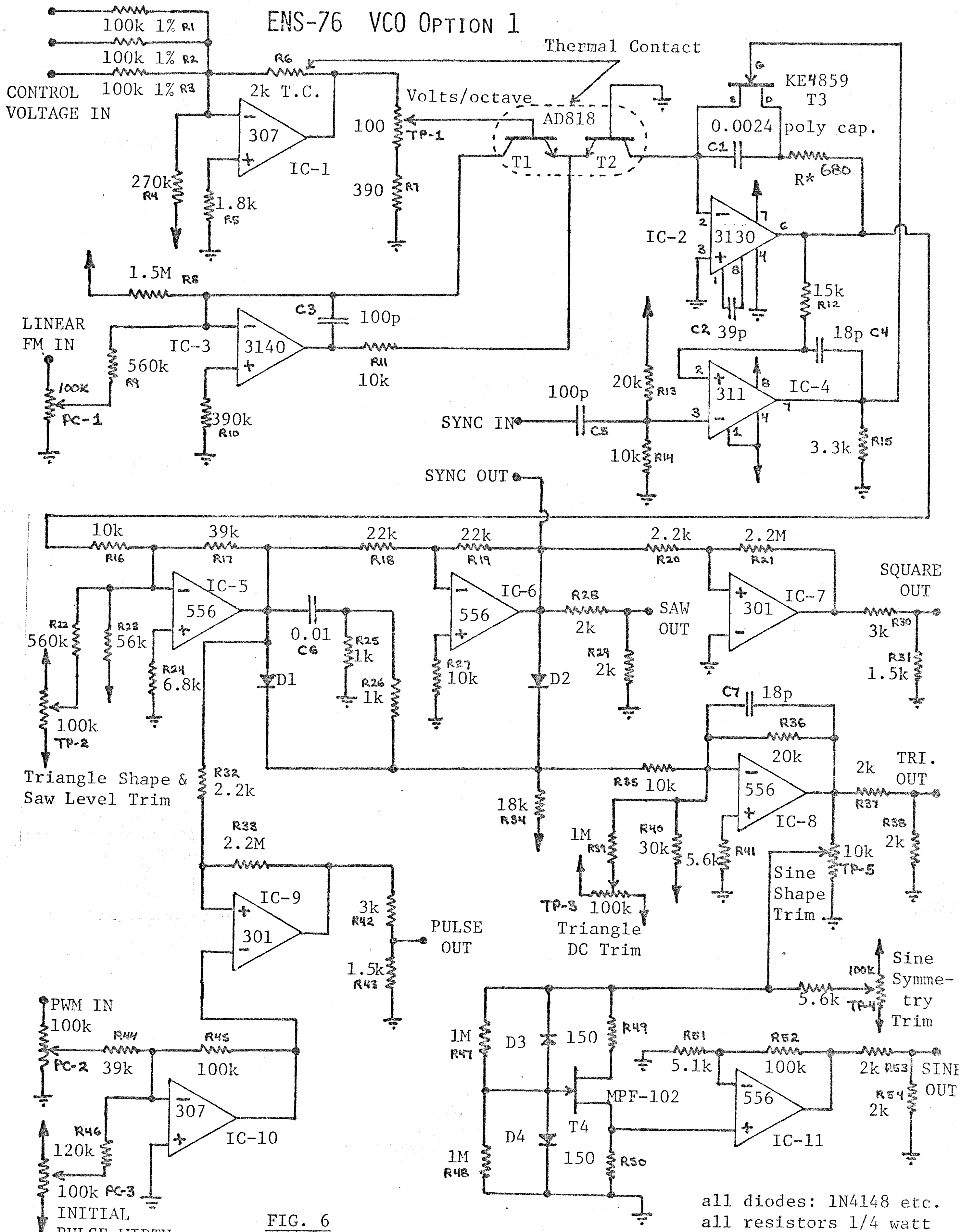
The exponential current source (IC-1, IC-3, T1 & T2) is a standard design which we have used many times before. Here we have improved things as much as possible by using the CA3140 op-amp to regulate the reference current, and the AD818 pair as the converting transistors. No provisions are made here for high end compensation of the exponential stage, but standard temperature compensation is made.

The basic oscillator is a sawtooth (ramp) relaxation oscillator formed from IC-2 and IC-4, and is only slightly changed from the original Mikulic design. IC-2 forms an integrator where the exponential current from the collector of T2 causes capacitor C1 to charge. For the moment, assume that R* is zero ohms. When the output of IC-2 reaches +5, the voltage on pin 2 of IC-4 is the same as the reference on pin 3 (as determined by voltage divider R13-R14), and as the voltage starts to rise above +5, comparator IC-4 goes from -15 to ground (pulled up by R15). This turns on the FET switch T3, and capacitor C1 begins to discharge rapidly. In general, the capacitor would discharge a little below +5 and the comparator would then shut off the FET switch. This would result in an output consisting of a high frequency oscillation of low amplitude centered about +5. This is where the capacitor C4 comes in. When the comparator switches high (to ground that is), the capacitor voltage is +20 volts . (-15 from the comparator, and +5 fed in from the ramp through R12). This will cause to comparator to remain high until C4 discharges to +5 volts (starting at +20 and being discharged through R12 to pin 6 of IC-2, which is going from +5 to zero). The time constant is thus something like 1.4·R12·C4, which is something like 400 ns. This is the time interval during which the FET switch will be on. This is long enough to completely discharge the capacitor for all practical purposes. Note finally that the discharge can be initiated a little early by the Sync. control input. A negative going pulse here will lower the reference a bit and institute the reset cycle.

The sawtooth-to-triangle converter consists of IC-5, IC-6, and IC-8. IC-5 takes the zero to +5 ramp from IC-2, amplifies it by a factor of 4 and level shifts it. The result is an inverted sawtooth from +10 to -10. IC-6 is an inverter which gives back the normal (rising) sawtooth from -10 to +10. This is brought out as the sawtooth output, attenuated and impedance adjusted by R28-R29 to a ramp from -5 to +5 with an output impedance of 1k. The diode arrangement of D1 and D2 selects the higher of the two waveforms - the sawtooth or the inverted sawtooth. This is easily seen to be a triangle from +10 to zero. IC-8 amplifies this by a factor of two and level shifts for zero DC average. The output of IC-8 is thus a +10 to -10 triangle. The output is obtained through R37 - R38 as a ±5 triangle. We have used a "counterglitch" circuit here to remove (to a large degree) the switching glitch caused by the diodes. This counterglitch is provided from the inverted sawtooth through C6 and R26. Some minor adjustments of the value of C6 may be desirable in some setups. R34 pulls down the diodes, resulting in a better positive "point" on the triangle output, and C7 acts to further remove any switching glitches.

Rectangular waveforms are provided using uncompensated 301 type op-amps (or 748 types can be used). The square is provided by IC-7, and a variable pulse is provided

ENS-76 VCO OPTION 1



all diodes: 1N4148 etc.
all resistors 1/4 watt
PC = Panel Control
TP = Internal Trimmer

FIG. 6

All Diodes: 1N4148

by IC-9, relative to a reference voltage level provided by IC-10. This is all very standard, but keep in mind that both IC-7 and IC-9 are left completely uncompensated so that they will go as fast as possible (no capacitor between pins 1 and 8), and the positive feedback provided by the 2.2M resistors relative to the 2.2k input provides mild hysteresis for additional "snap" and noise rejection. The outputs of IC-7 and IC-9 range from +15 to -15, so 3k-1.5k voltage dividers are used to scale these to ±5 volt levels.

Finally, we use the FET type sinewave shaper as driven by the triangle waveform. We chose this rather than the CA3080 shaper (used in later options) because it gives a slightly better looking waveform, and because we do have the ±10 volt triangle to drive it. It normally requires a 6 to 7 volt signal to reach the non-linear region.

It is probably obvious that since we are using ±10 volt levels inside the circuit, it is easy to bring these out. For easy reference, the conversion is listed below:

RESISTOR	AS IS ±5	CONVERSION TO ±10
R28	2k	1k
R29	2k	Omit
R30	3k	1.5k
R31	1.5k	3k
R37	2k	1k
R38	2k	Omit
R42	3k	1.5k
R43	1.5k	3k
R53	2k	1k
R54	2k	Omit

At this point, we want to say something about the resistor R*, which is the resistor that provides high frequency compensation by Franco's method [See S. Franco, "Hardware Design of a Real-Time Musical System", Dept of Computer Science Report UIUCDCS-R-74-677, Univ. of Illinois, Urbana-Champaign]. The principle is basically as follows: There is a finite switching time which causes an oscillator to go flat on the high end. The higher frequencies correspond to higher charging currents. Thus, by inserting a resistor in series with the integrating capacitor, an additional voltage is impressed across the R-C combination, and this causes the oscillator to reach its peak voltage a little earlier. A full analysis (see reference above or chapter on VCO's in <u>MEH</u>) will show that this is an exact correction for a constant reset time, and that the R*·C1 product should be equal to the switching time, which we saw above was about 400 ns. This gives a value of R* of about 166 ohms. This is a good starting value. In addition, it turns out that the error due to the bulk base-emitter resistance of the exponential current stage transistors can be corrected by a term that is the same order as the delay time correction. Thus, by making R* larger than is necessary to correct for delay time, we can also do some correction for bulk resistance. Of course, all the analysis in the world is generally no substitute for an actual experiment, and we can easily find the value for R* by an experiment - basically as shown in Fig. 5.

The data from an actual experiment is shown in Fig. 7. Here we have tabulated control voltage, approximate frequencies, and the ratio of frequencies that we actually observed for a one volt change of control voltage. Ideally, this should be 2.00 in all cases. By studying these figures, you can see that 680 ohms of Franco compensation pretty much solves the problem over the audio range. It is well not to use much more resistance than this as the method does result in some imperfections in the waveforms, and the oscillator may stall at low frequencies. Note however that the imperfections that result from the 680 ohm resistor are not too important as they only become appreciable at frequencies above 5 kHz or so, and the harmonic content in waveforms at such frequencies is of little importance because much of it is beyond the upper frequency limit of the ear.

FIG. 7

CONTROL VOLTAGE	APPROX FREQ.	UNCOMPENSATED	680 OHM FRANCO COMP.
-1.00	10		
		2.00	2.00
0.00	20		
		2.00	2.00
+1.00	40		
		2.00	2.00
+2.00	80		
		2.00	2.00
+3.00	160		
		2.00	2.00
+4.00	320		
		2.00	2.01
+5.00	640		
		2.00	2.00
+6.00	1280		
		1.99	2.00
+7.00	2560		
		1.99	2.00
+8.00	5120		
		1.97	2.00
+9.00	10240		
		1.93	1.97
+10.00	20480		

It should not be too difficult to construct this circuit. A little care should be used handling the MOS op-amps (CA3130 and CA3140), and of course be careful with the expensive AD818 pair. All op-amps are powered between +15 and -15 except for IC-2, the CA3130. Also, be sure to note the unusual pin connections for the LM311 comparator, and be sure not to forget the pull-up resistor R15. All the type 4859 FET's we have seen have the base diagram shown in Fig. 8, as seen from the bottom view. This includes the 2N4859, the KE4859, and the PN4859. Some may have three in-line wires at the very base, but will have the triangular diagram further out.

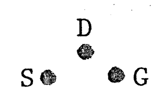


FIG. 8

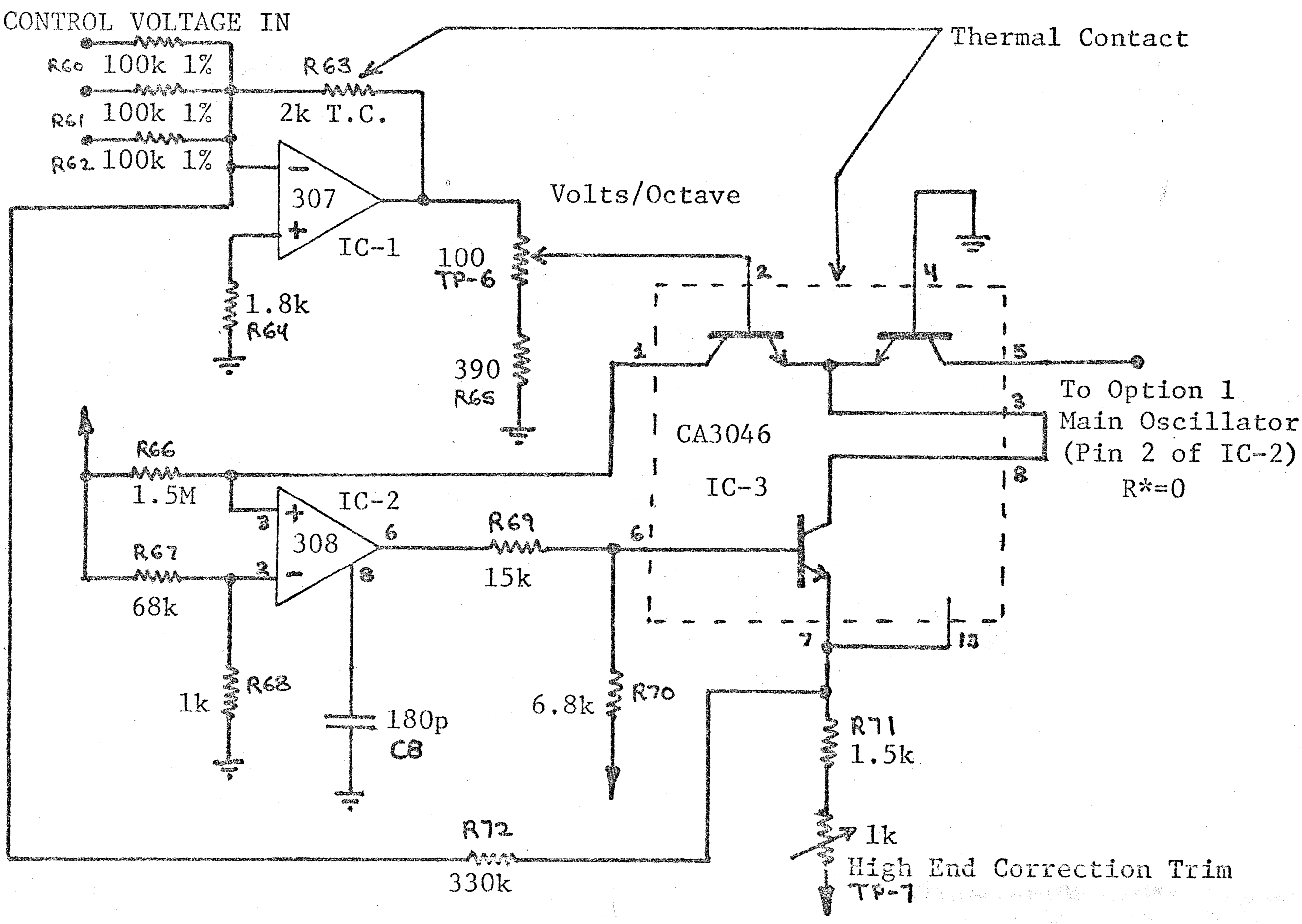
ENS-76 VCO Option 1a

Option 1a is a variation on Option 1. In 1a we are using the original exponential current source given by Terry Mikulic in EN#62 which uses Moog-Hemsath compensation rather than Franco compensation. Thus, we have only to use the exponential stage of Fig. 9 connected to the oscillator and waveshapers of Fig. 6, and make R*=0. This circuit also works quite well. The principal advantage is the lower cost of the CA3046 array as compared to the AD818 pair, and the principal disadvantage is that it has one additional trim pot to tune up. Some builders may want to leave in R* = 150 ohms for Franco compensation of the reset time, and use the correction shown here for only the bulk resistance correction. We have not looked at this carefully to see which is the better way.

Be sure to note that IC-2 is an LM308 type op-amp. We suggest only this one here. A 307 with no external compensation may work with a little oscillation at the output, but a CA3140 does not work, and placing a capacitor between pins 3 and 6 of the CA3140 will of course cause additional oscillation rather than compensate. There may be a way of compensating with the CA3140, but unless you love experimenting, stick with the LM308 here with the 180 pf compensation shown. Also, don't forget to connect up the substrate pin (pin 13) of the CA3046 as shown, or connect it through about 10k to the -15 supply.

ENS-76 VCO Option 1A

FIG. 9



To adjust the tracking of Option 1a, you first set the high end correction trimmer to its minimum value and tune the 100 ohm volts/octave control for 1 volt/octave in the low frequency (say 100 Hz to 200 Hz) range. Next, adjust the input control voltage so that you are in the upper frequency range (say the 7500 Hz to 15,000 Hz octave) and check the ratio here. It should be less than 2.00. Now, adjust the 1k High End correction pot in the direction so that the series resistance of the pot and R71 increases. This will increase the feedback. Once you get a one volt/octave response up high, recheck the lower octaves. There should be no change, and the overall tracking should be quite good.

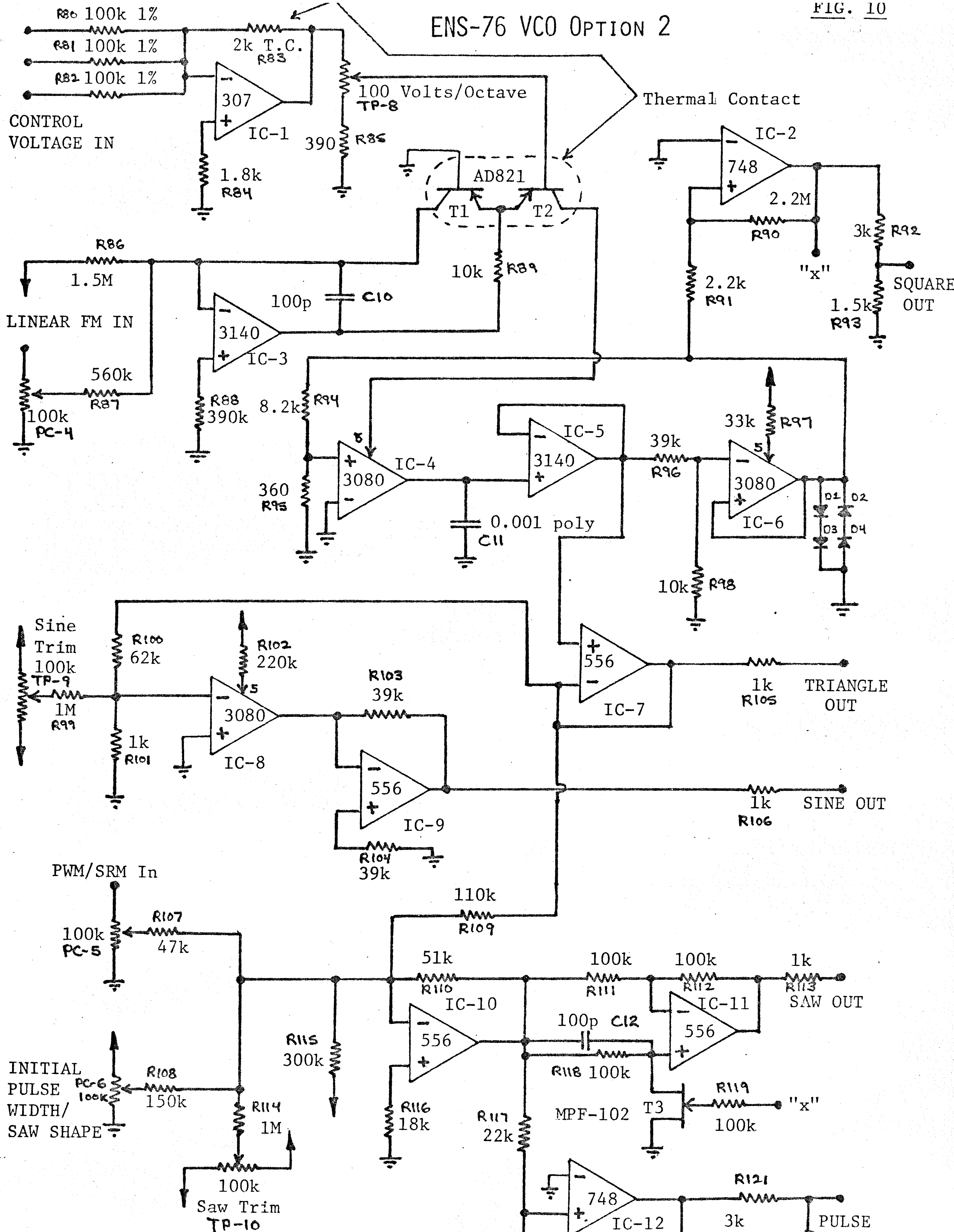
ENS-76 VCO Option 2

VCO Option 2 is shown in Fig. 10. This option, like Option 1 and Option 1a above is a real "workhorse" option. Even if you decide to make mostly Option 1 oscillators, you should have at least one Option 2 as it has several additional features of interest.

Basically, Option 2 consists of an exponential current source IC-1, T1 and T2, IC-3; Triangle-Square oscillator IC-4, IC-5, IC-6; and associated waveshapers.

We have used the CA3080 as a current reversing switch before (EN#46 for example). The CA3080 must be driven by a PNP transistor, and hence, we have had to use the AD821 matched PNP pair, which works just fine. However, we have also had to add an extra inverter or current mirror to get higher voltages to correspond to higher frequencies, which is the usual case. These extra elements of course add to the possibility of additional drift. A much simpler solution is to just reverse the base connections of

ENS-76 VCO OPTION 2



All diodes: 1N4148 etc.
PC= Panel Control
TP= Trim Pot

the two exponential converter transistors. Note that this means that the control voltage (as scaled to about 18 mV/Oct.) is applied to the base of the same transistor that supplies the actual exponential current. Compare this with Option 1 in Fig. 6 which uses an NPN pair. This simplification can be applied to other circuits we have given as well.

The basic oscillator consists of IC-4, a current reversing switch driving integrating capacitor C11; a FET input op-amp voltage follower IC-5, and a fast Schmitt trigger. Note that diodes D1 to D4 limit the output of IC-6 to either about +1 or -1, and that this voltage is fed back to the + input of IC-6. Suppose first that the + input of IC-4 is positive, driven by the output of IC-6. This means that the control current into pin 5 of IC-4 is being driven into C11. Thus the voltage across C11 is increasing in a positive direction, and IC-5 is following this voltage. When the output of IC-5 reaches about +5 volts, voltage divider R96-R98 will be supplying about +1 volts to the - input of IC-6, and the output of IC-6 will go to -1 volts. This means in turn that the capacitor voltage will start to ramp downward. The cycle repeats producing a triangle wave of 5 volt amplitude.

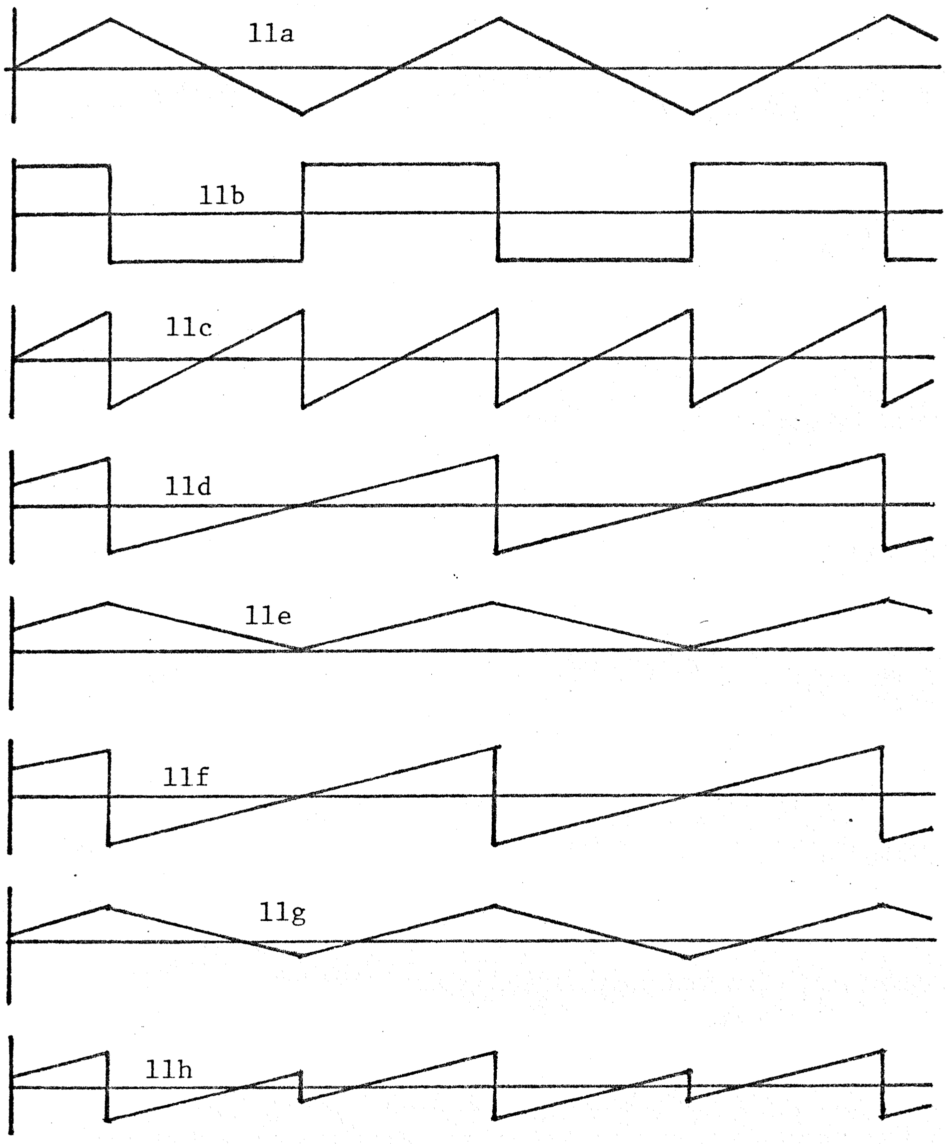
We have used this type of basic oscillator before, but have not used the CA3080 as a Schmitt trigger. In fact, it appears to be a good one and is plenty fast for an audio frequency oscillator. One possible drawback is the fact that the diodes D1 to D4 determine the amplitude of the triangle, and thus indirectly the frequency. Since silicon diodes exhibit approximately a -1.7 mV/°C change of forward voltage drop, this is of some concern, because this is about .28%/°C. In a rough experiment, we measured a drift of only about 1/3 this amount for the entire oscillator. It would seem that this deserves more study, but there may be no real problem.

Since the CA3140 is not suitable for driving 1k loads in our application (see EN#69, pg. 13), we buffer the triangle with a 556 before bringing it out. You could use the 556 as IC-5, omitting IC-7, but the CA3140 is excellent as the follower on the capacitor due to its low bias current requirements.

IC-8 and IC-9 form a triangle-to-sine converter using the overdriven differential amplifier principle (see MEH, Chapter 5b (18)). The sine trim is adjusted for symmetry of the upper and lower portions of the waveform. By ear, one just adjusts for lowest distortion. In fact, the adjustment shown removes only even harmonics, but the 62k-1k voltage divider pretty well optimizes the driving voltage for lowest odd harmonic distortion. Note also that a square wave is obtained using IC-2 in a conventional manner.

It remains to bring out the pulse, and to convert the triangle to a sawtooth. We will do these at the same time as we want our Pulse Width Modulation (PWM) setup to be used also in a Symmetrized Ramp Modulation (SRM) setup. The principles involved are illustrated in Fig. 11. A discussion of the original idea was given by Bill Hartmann in EN#67. Fig. 11a shows the original triangle output while Fig. 11b shows the square wave "x" in the circuit. If we consider that the square can be made to invert the triangle wave if it (the square) is negative, and to not invert if it (the square) is positive, we can produce the double frequency sawtooth of Fig. 11c using a circuit like that of IC-11 and surrounding components in Fig. 10. We did this in our older oscillators, and then added a portion of the square wave to get the original frequency back (see Fig. 11d). Bill Hartmann suggested that instead we first add a DC voltage to the triangle so that it touches zero, but is otherwise always positive (Fig. 11e) and then invert-or-not-invert the waveform using the square. This gives the original frequency sawtooth as before (Fig. 11f). Now, by allowing the DC offset to take on a general level (Fig. 11g for example), a Symmetrized Ramp results (Fig. 11h). By varying the DC level, we get modulation of the symmetrized ramp. This is exactly what we do in the Option 2 circuit. The offset is provided by IC-10. It is then a trivial matter to obtain Pulse Width Modulation (PWM) by zero crossing the offset triangle (using IC-12).

FIG. 11



It is probably easiest to see how Symmetrized Ramp Modulation works by studying Fig. 12. In Option 2, both the SRM and PWM processes are driven by the offset triangle. The DC offset of the triangle is the modulation voltage. In Fig. 12, the triangle is shown with five different DC levels. Above the offset triangles is shown the square wave (point "x" of Fig. 10) which determines whether the offset triangle is output in its normal or inverted form. A full swing of the DC offset changes the waveform from a normal rising sawtooth, through a double frequency sawtooth, back to another normal sawtooth 180° out of phase with the original.

The pulse waveform is quite easy to understand, as it is just a zero-crossed version of the triangle. As we have shown it, there is no output from the pulse output when the triangle is fully positive, but there is a very narrow pulse out when the triangle is a little negative. This is really determined by the way the "Saw Trim" pot is set. Actually, in our setup this was the way it came out when we set the best saw shape

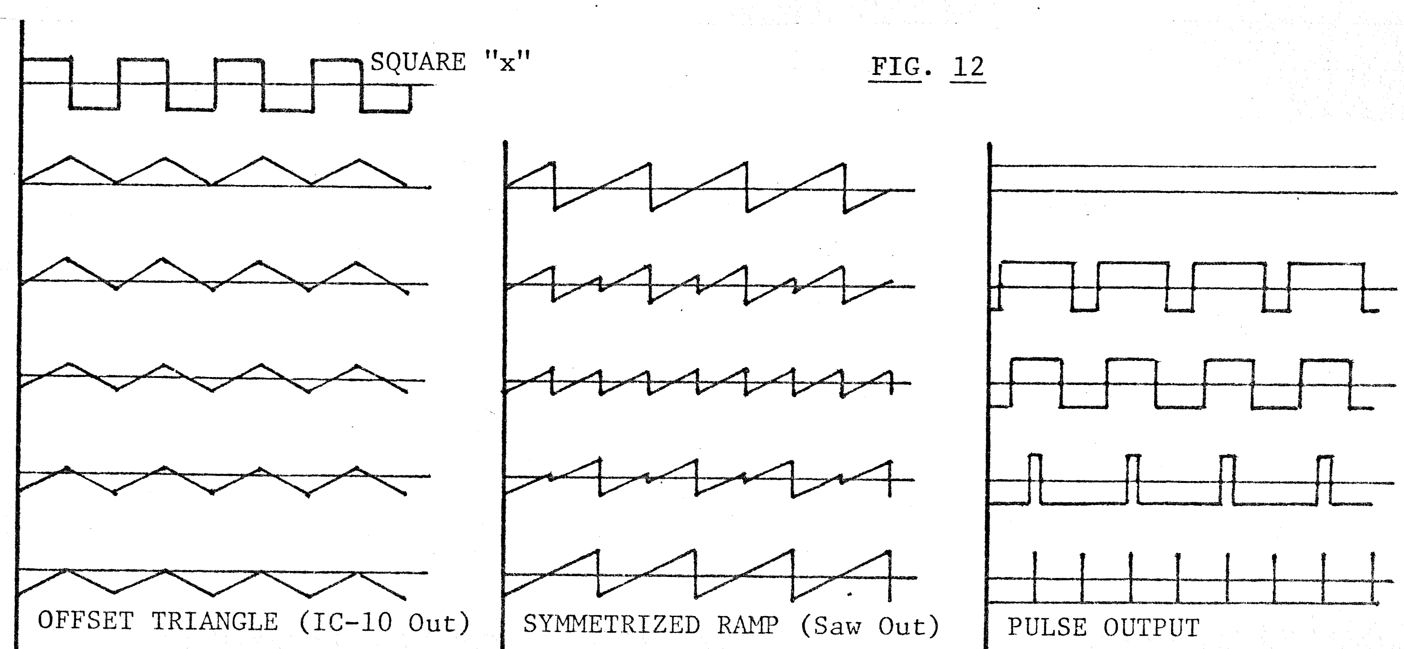


FIG. 12

If you prefer, you can balance things out so that you have no pulses out at all when the normal sawtooth is set, or so that you have narrow pulses out for both normal sawtooth positions. As we have set it up, you have a choice. In one normal sawtooth position, you can get a DC output of +5 volts from the Pulse Out. In the other normal sawtooth position, you get narrow pulses. The feeling is that in many cases, the players will be using mostly normal waveforms, and it may be confusing if there is no output from the pulse at the time when the sawtooth is quite normal. What it boils down to is that you have a choice as to which extreme of the pot rotation you choose to mark as normal sawtooth. Note that we have added a little extra hysteresis to this pulses circuit (we made R117 = 22k rather than 2.2k) because of the closeness of the offset triangle to ground. By the way, R109 really is 110k in our setup, not 100k.

The volts/octave control is set up in the normal manner: first you adjust a lower octave and then check the higher octaves. In our setup, we actually found that the high-frequency performance went up, rather than down as you would normally expect. It would probably not be too difficult to slow this down if it is necessary. Note in particular that over the normal audio range, the performance is quite good. The data table is given in Fig. 13.

CONTROL VOLTAGE	APPROX. FREQ.	RATIO
-8.00	1.5	2.00
-7.00	3.0	2.00
-6.00	6.0	2.00
-5.00	12.0	2.00
-4.00	24.0	2.00
-3.00	48.0	2.00
-2.00	96.0	2.00
-1.00	192	2.00
0.00	384	2.00
+1.00	764	2.00
+2.00	1528	2.01
+3.00	3056	2.01
+4.00	6112	2.01
+5.00	12224	2.01
+6.00	24448	2.02
+7.00	48896	

FIG. 13 Option 2 Data

Note that for the normal sawtooth, there is a glitch in the midpoint of the sawtooth due to switching. We found that the 100pf capacitor C12 did a good job of greatly reducing this glitch. The builder may want to play around with this value a little.

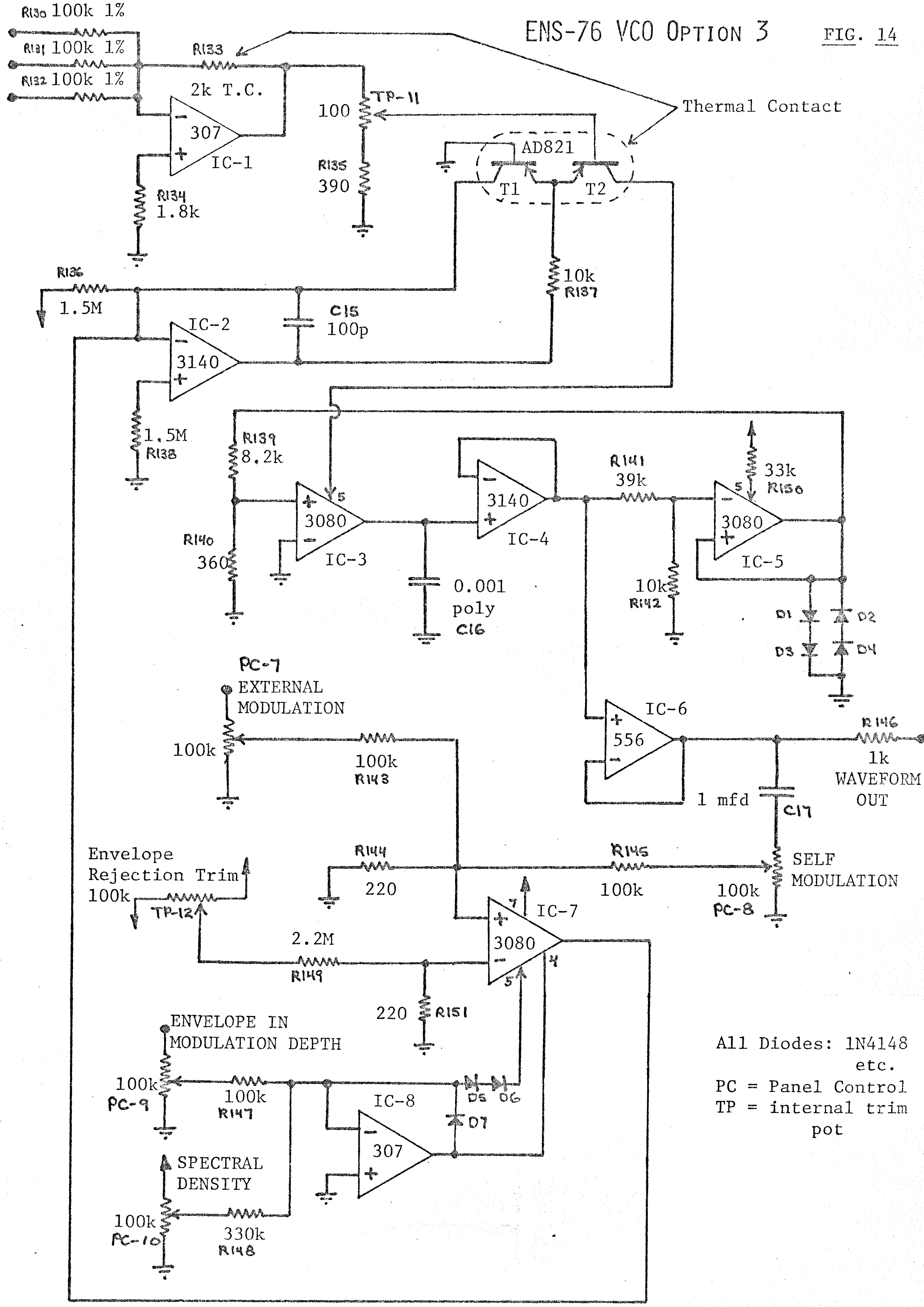
A number of additional changes to the circuit are possible. For example, if you add a zero-cross detector to the triangle out of IC-5, you can use this to drive point "x" instead of the output of IC-2. A switched option would be suggested if this is done. The result is a whole new group of waveforms is you can easily show with a few sketches, since the new square wave is out of phase with the square wave out of IC-2 by 90°. Also, by inverting the square wave out of IC-2, you get inverted rather than normal sawtooth waveforms. It is also interesting to form mixtures of pulses and symmetrized ramps, and you may want to make this a standard feature.

ENS-76 VCO OPTION 3

The circuit of VCO Option 3 is shown in Fig. 14. This VCO is quite simple, and in fact can even be simplified more in some cases. The circuit is simple because we have included no waveshapers in the design. Instead, linear frequency modulation is used to produce a variety of waveforms. Note that the circuitry around IC-1, T1, T2, IC-2, IC-3, IC-4, IC-5, is identical to that of Option 2. The remainder of the circuit is really a VCA which controls the amount of output signal that is fed back to "self-modulate" the VCO. There are two points to note about the way self-modulation is used here: First, it is necessary to feed in the waveform through a linear input to avoid the well known pitch shift. Secondly, even though we are using a linear input, it is necessary to use AC coupling in the feedback line. If this is not done, the resulting asymmetry caused by the self-modulation will cause another pitch shift. The result of self-modulation when applied with these conditions is that the frequency remains the same as the modulation depth increases, but the waveform is greatly altered resulting in a higher harmonic density. The general type of warping of the waveform is illustrated in Fig. 15 where self-modulation is applied to the triangle wave. Note that the waveform changes from a low harmonic triangle to a very high harmonic pulse-like

ENS-76 VCO OPTION 3

FIG. 14



All Diodes: 1N4148 etc.

PC = Panel Control

TP = internal trim pot

waveform. While self-modulation is an important feature of this design, because we are using it to get rid of many waveshapers, the circuit has other important capabilities as well. The external modulation input will accept any external waveform. We DC coupled this one on the assumption that only balanced waveforms would likely be used as modulating signals. This is likely because the waveforms from other VCO's are usually balanced, except for the pulse of course. A capacitor similar to C17 could be used to AC couple the external input, but it is felt that DC coupling is important here as very low frequency modulating signals may be used.

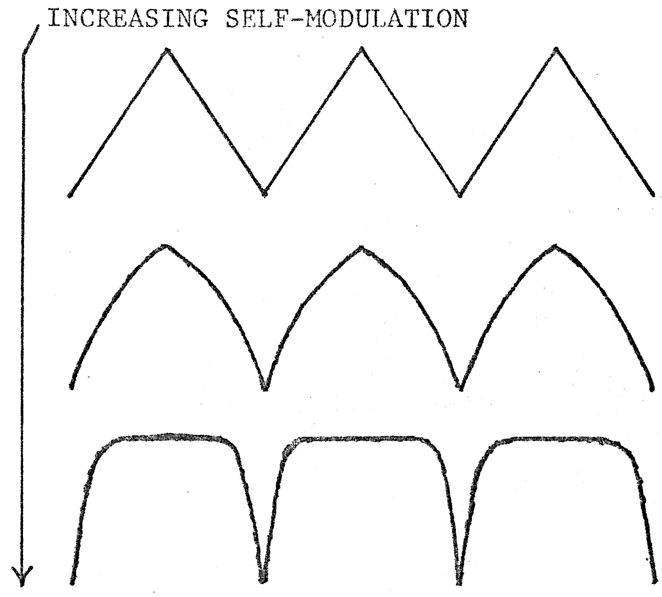


FIG. 15

While self-modulation produces harmonic spectra only, use of external modulation permits the user to obtain spectra with frequency components that are not harmonically related to a fundamental. These have been shown to be very useful for producing the sounds of bells and other percussive sounds. It is also true that dynamic depth of the modulating signal is very useful. This is why we have put a VCA inside the VCO. The user applies a control envelope to the envelope control, and the depth of modulation is controlled by this envelope. As with any VCA, it is desirable to trim out the VCA for maximum envelope rejection, and this is particularly important here because any low frequency voltage that gets through will result in a pitch shift. For more information on the VCA part of the circuit, see EN#63.

There are a number of possible alterations to this circuit which make sense in certain cases. For a very simple VCO, the VCA can be replaced with just a manual pot (or two) as indicated in Fig. 16. This will result in a spectral density control similar to the earlier design, and waveforms as shown in Fig. 15 can be produced as static rather than dynamic versions. This would seem to make a very simple VCO for a small portable synthesizer. In addition, some users might like to add a sinewave shaper to the output of IC-6 and feed this back rather than the triangle. This would mean that the spectral density control would change the waveform from a reasonably pure zero-harmonic sine wave to a very high harmonic density pulse. The sinewave shaper of Option 2 (IC-8 and IC-9 of Fig. 10) would serve nicely. Because our interest in this design was mainly in the dynamic possibilities, we were not too concerned with getting to a very low harmonic content. But, of course, there is no reason not to add the sine shaper to the full circuit of Option 3. Another possible addition to the circuit would be to add a zero-cross detector to the output of IC-6 so that some square and pulse waveforms could be produced. The circuitry around IC-7 of Option 1, Fig. 6 would be suitable for this purpose.

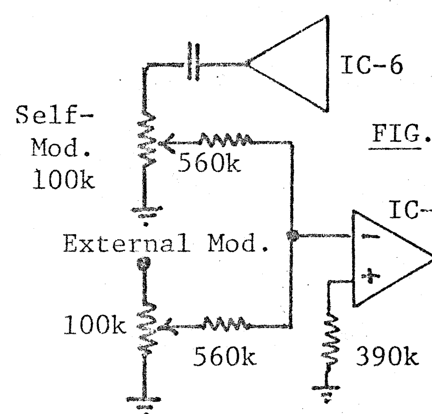


FIG. 16

The circuit is not difficult to build, and tuning to one-volt-per-octave is very similar to Option 2. This tuning should be done with all modulation and envelope pots set to their minimum (full off) values. There should be little or no leakage of current from the output of the CA3080 in this case. To set the envelope control rejection, turn up the self modulation full value, run the Initial Modulation Depth pot up and down, and adjust the envelope rejection until no pitch shift is heard as the Initial Modulation Depth pot is varied. Our setup of this circuit was a little unstable at first - it needed some extra bypass capacitors to settle down.

The circuit diagram of VCO Option 4 is shown in Fig. 19 on page 18. This VCO is an extension of the Option 3 circuit. This VCO has the capability of Linear Frequency Modulation through zero and on to negative frequencies. To understand exactly what is going on here, first consider the typical linear input stage as shown in Fig. 17, which is from Option 1. The linear input can reduce the current into the summing node to zero, at which point the oscillator stops. If the linear input tries to reduce the current further, the oscillator remains stalled. We will want to say more about the meaning of negative frequencies in a future newsletter, but for now we will note that one of the things we will have to do to keep the oscillator running for negative control sums is to add a full wave rectifier to the linear input. Bob Moog, who examined this type of oscillator several years ago suggested that the full wave rectifier should be made with analog switches rather than with diodes. This is what we have done here. The second requirement for through-zero linear FM is that at the point at which the linear control sum changes sign, the phase of the output waveform should back up. This is a little hard to visualize, but Fig. 18 may be of some help. Here we are supposing that the linear control sum (that is, the voltage at the output of IC-3) is changing from a positive value to a negative value by a smooth transition. If we simply add a full-wave rectifier to the control sum voltage, the advance of phase slows down, stops momentairly, and then continues in the same direction, speeding up. This is indicated in Fig. 18a. On the other hand, if the phase is to back up, the advance of phase shown in Fig. 18a remains the same up to the point where the control sum is zero and the oscillator stops. But then, the waveform is as in Fig. 18b where the phase effectively reverses direction. One might rightfully ask if it really makes any difference. This oscillator provides an easy way of testing to find out. The answer is that it does. With the phase reversal, the modulation depths seem much deeper, and there is much more harmonic content apparent. I put a switch in my oscillator to make it easy to change or not, and the outputs without phase reversal were relatively bland by comparison. As you might expect, for very slow modulation frequencies, this phase reversal can not be detected. This is because all the time the oscillator is passing between about 15 Hz to -15 Hz the output is inaudible, and this apparent pause is long enough so that any realization of the former phase is forgotten. Note also that this circuit is only one approach to through-zero linear FM. An approach similar to this one was given by Douglas Kraul in EN#62, and a beat frequency approach was used by Jan Hall in EN#69.

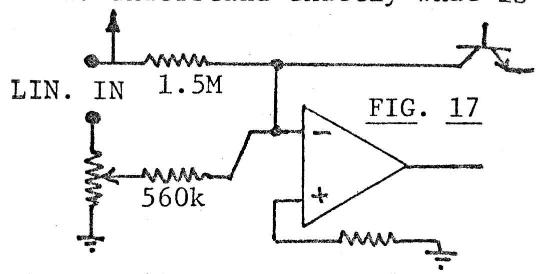


FIG. 17

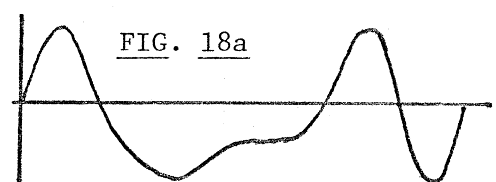


FIG. 18a

No Phase Reversal

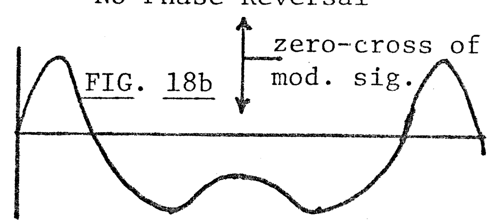


FIG. 18b

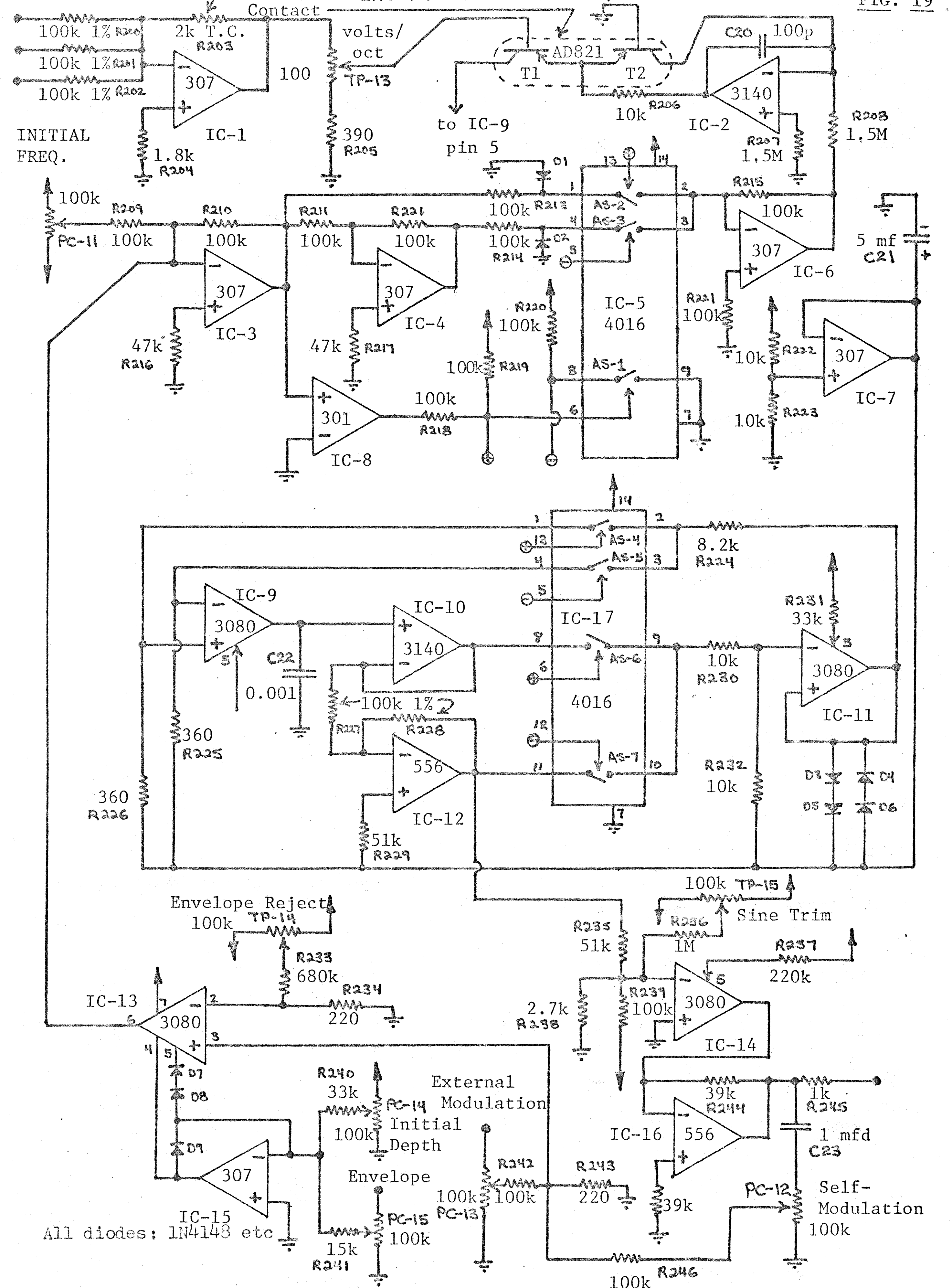
With Phase Reversal

Before we examine the circuit in detail, we should note that we have seen much of it in earlier options. The exponential stage (IC-1, IC-2, T1 and T2) is familiar. IC-14 and IC-16 are a sinewave shaper, and IC-13 and IC-15 form the VCA, as in Option 3. If you stare at IC-9, IC-10, IC-11, IC-12, and IC-17 a bit you will see that this is basically the same Triangle-Square oscillator used in Options 2 and 3. The difference is that there is the analog switch in the middle (IC-17) and the oscillator runs with a reference voltage of +7.5 volts, which is supplied by IC-7. That's about all there is to it.

To see exactly how the oscillator works, let's work through two cases. We will assume that the main exponential controls are set to a constant voltage. First, we assume the input to the linear control is such that the control sum is positive.

ENS-76 VCO Option 4

FIG. 19



Since the control sum (output of IC-3) is positive, comparator IC-8 is at +15, and thus the tie point ⊕ is positive 15 which we shall consider "Logic High" for the system. This closes analog switch AS-1 and provides ground potential ("Logic LOW") at the ⊖ tie point. AS-1 is thus just a logical inverter. Note now that AS-2 is also closed, so IC-6 provides an inverted version of the control sum to R208, which supplies the reference current to the exponential converter. Now, also consider that AS-4 and AS-6 are closed and you see that we have our standard Triangle-Square oscillator in operation. The only differences are that here we are oscillating relative to +7.5 volts, and R230 is 10k in this case, so the amplitude of the oscillation is only 2 volts instead of 5. We had to move this up so that the analog switches would work properly. Note however that all the op-amps are still powered between +15 and -15, we have just changed the reference level for the oscillator.

Next, we will assume that the control sum out of IC-3 has gone negative. IC-8 now goes to -15 and thus the ⊕ tie point goes to ground, AS-1 opens, and the ⊖ tie point is pulled high through 100k resistor R220. Thus, the ⊕ tie point is Logic Low and the ⊖ tie point is Logic High. An inverted version of the control sum appears at the output of IC-4, and since the sum is negative, this output is positive. Since AS-3 is now closed, this means that IC-6 is now presenting the control sum as a negative voltage to R208, which is what the exponential converter wants. Thus it can be seen that IC-3, IC-4, IC-5, IC-6, and IC-8 form a full wave rectifier. Now, looking down at the actual oscillator again, since the ⊖ tie point is high, AS-5 and AS-7 are closed. In this condition, the circuit still oscillates in a normal manner since there is a double inversion: IC-12 inverts the waveform, and the - rather than the + terminal of IC-9 is receiving the square wave from IC-11.

Now, the real difference here is seen when we consider what happens when the control sum changes sign. In this case, the triangle waveform will be at some voltage and will be moving in one direction, let us say from - to +. As the control sum reaches zero, the triangle waveform output will come to a stop, all analog switches will reverse, and when the control sum goes negative, the voltage at the triangle output will start moving again, but this time in the opposite direction, instead of finishing the cycle it was working on.

The circuit should give no real problems to the builder, but it is fairly complex in the sense that one small error can halt things. In the earlier options, usually the oscillator does run, and you can trace from there. So be careful not to make any wiring errors. All the adjustments that need to be made are the same as those done in earlier options. Do not omit the diodes on pins 1 and 4 of IC-5, as otherwise the negative voltage will confuse the analog switches. Also note that the triangle out of IC-12 is level shifted and scaled down to a 78 mV level by resistors R235, R238, and R239. If you are not satisfied with the shape of the sine wave, adjust the value of R238 up if you need more rounding, and down if you need less rounding.

When you get the oscillator running, some experimenting is in order. It is suggested that you first set the initial frequency pot slightly off center, and apply a slowly varying signal (say 1/2 Hz) to the external modulation input. Use no envelope and no self-modulation. Now turn up the "Initial Depth" control and listen to the output. The modulating signal will cause the frequency to go to one extreme, return to zero with a weak thumping sound, and then again become audible and move to another extreme. Since the initial frequency control is off center, the two extremes will be different. If you now apply some negative voltages to the exponential controls so that the oscillator runs very slowly, you will be able to watch the output move slowly on a scope, and by changing the initial frequency from one side of its center position to the other, will be able to observe the oscillator change direction in mid cycle. This should convince you that the oscillator is working properly, and you can go on with other experiments. This oscillator is most useful with modulating signals in the audio range applied externally. These are most useful for percussive sounds, particularly when the depth is changed using an envelope. Note that self modulation through zero is not possible in theory.

This is becaus self-modulation to zero is a command for the oscillator to stop. In practice, if you try to self-modulate to or through zero, you get a noisy unstable output, or a sort of tone burst behavior. There are many combinations of control settings that may result in erratic behavior, so you really have to sit down and see how things are supposed to work, or at least practice with the oscillator for a while. This oscillator is suggested for the user who already has some other oscillators, or for the user specializing in percissive sounds or other frequency modulation effects. If you want to demonstrate the effect of the phase reversal as opposed to just the full-wave rectification, install a double-pole, double-throw switch to supply the ⊕ and ⊖ tie points on IC-17 (only, leave IC-5 alone) with either the control signals as shown, or with just +15 to ⊕ and ground to ⊖.

ENS-76 VCO Option 5

Option 5 is a VCO which you may or may not find useful. It does illustrate certain principles. We don't really recommend it as a musical VCO for two reasons: First, it has only a sine wave output, and second, it's exponential response is not especially good on the high frequency end. It does provide a very good sine wave, and may be useful for a function generator, or for auditory experiments requiring sine wave test signals. We did not try it, but very likely two AD821 pairs in place of the CA3084 array would greatly improve the exponential performance.

The circuit of Option 5 is shown in Fig. 21. Very simply, it is one of our standard VCO designs producing a triangle waveform, followed by a standard waveshaper for the sinewave, and two poles of low-pass filtering to further improve the sinewave.

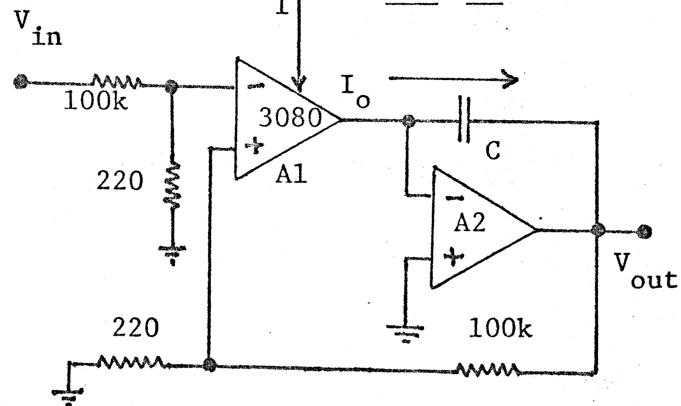
The circuit uses the CA3084 as a three output exponential current source - one output drives the VCO while the other two drive single-pole tracking filters. It was decided that the filters should track so that their 3db cutoff frequency would lie on the oscillator frequency. This assures that the harmonics of the ocsillator frequency will lie on the downslope of the filters response, and thus will be attenuated by the 6db/octave slope. To set these frequencies properly, we must know the frequency of the oscillator and of the filters as a function of current. This is determined as follows: First the oscillator. The current into the oscillator's capacitor is the same as the control current in magnitude. We use I = C(dv/dt) or dv/dt = I/C to give the rate of change of the capacitor voltage. We want the frequency which is cycles/sec or: cycles/sec = [volts/sec]/[volts/cycle]. We have volts/sec = I/C, and since the triangle has an amplitude of 2 volts, there are 8 volts/cycle. Thus:

$$F_{osc} = I/8C_{osc}$$

where C_{osc} is the capacitor in the oscillator. At the same time, the filters also receive the current I.

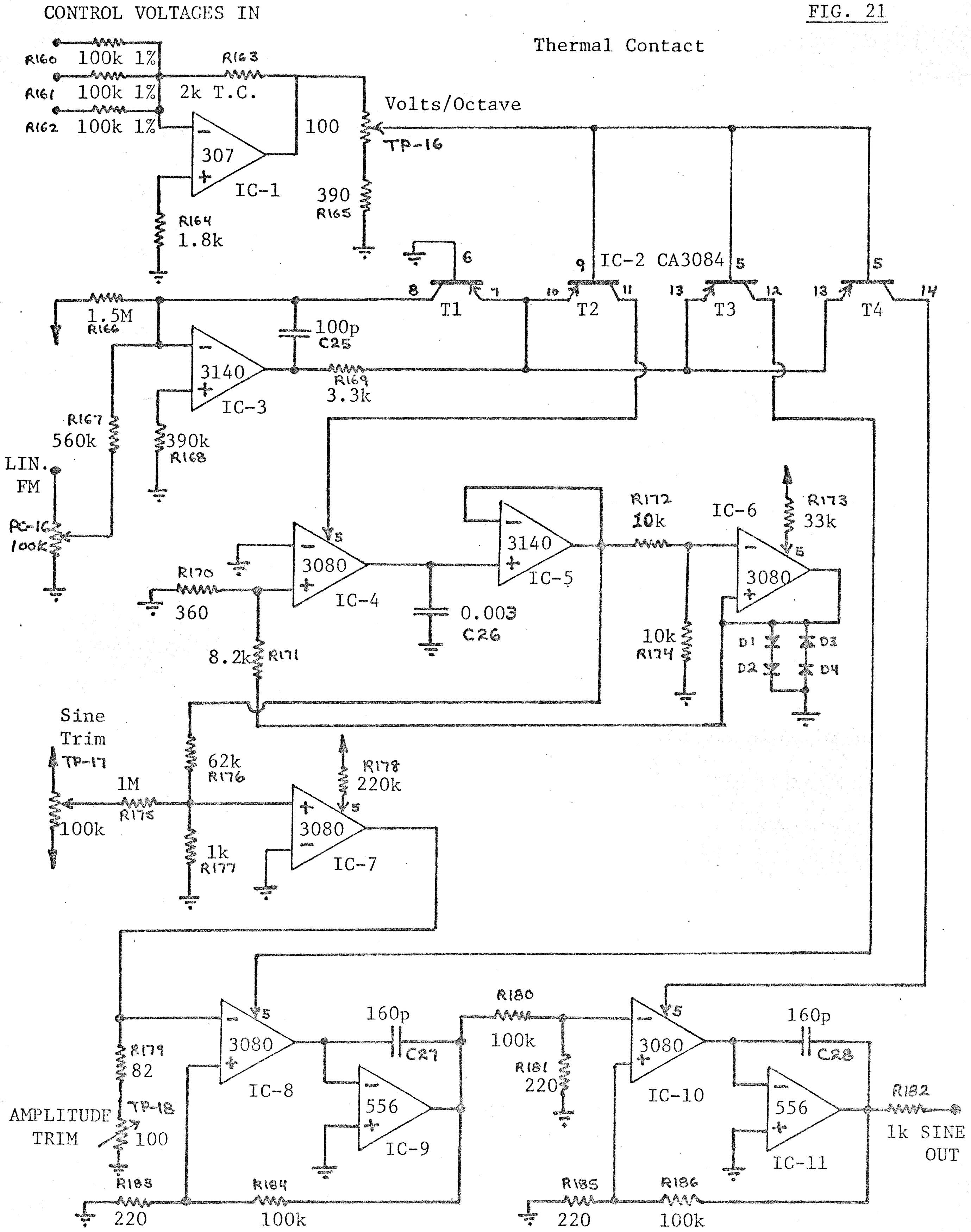
The circuit for the single-pole tracking low-pass filter is shown in Fig. 20. We have used this before, but have not developed the equation for the cutoff frequency. Here, we must do it so we know where to set the cutoff relative to the oscillator frequency. We start with the basic equation of the CA3080 in its linear region: $I_o = 19.2 \cdot I \cdot V_{diff}$ where V_{diff} is the voltage difference between the + and - inputs of the CA3080. From this we can easily show:

FIG. 20



ENS-76 VCO OPTION 5

FIG. 21



All Diodes: 1N4148, etc. PC = Panel Control TP = Internal Trim Pot

$$I_o = 19.2 \cdot I \cdot \frac{220}{100{,}220}(V_{out} - V_{in})$$

$$= (V_{out} - V_{in})/R_{eq}$$

where R_{eq} is the equivalent resistance of the CA3080 and is given by: $R_{eq} = 23.7/I$

Since the - input of A2 must be at ground, we can calculate V_{out} from I_o:

$$V_{out} = -I_o(1/sC) = (V_{in} - V_{out})/sCR_{eq}$$

which can be solved for $T(s) = V_{out}/V_{in}$:

$$T(s) = \frac{1}{1 + sCR_{eq}}$$

To get the frequency response, we calculate $|T(j\omega)| = [T(j\omega)\cdot T(-j\omega)]^{1/2}$ and set this equal to $1/\sqrt{2}$ to get the 3db frequency. This gives:

$$\omega^2 R_{eq}^2 C^2 + 1 = 2 \qquad \text{or} \qquad \omega = 1/R_{eq}C$$

We thus have for the 3db frequency of the filter:

$$F_{filt} = \frac{1}{2\pi R_{eq}C} = \frac{I}{2\pi(23.7)C} = \frac{I}{149C}$$

Now, we want to set the filter's 3db frequency equal to the frequency of the oscillator:

$$I/8C_{osc} = I/149C_{filt}$$

The value of the capacitor for the filter is this: $C_{filt} = 0.054\ C_{osc}$

Since we have chosen for the oscillator a capacitor of 0.003 mfd, we get a value for the filter of about 160 pf.

So we want to use two filters of this type. However, there is no real sense in doing a current-to-voltage conversion on the output of IC-7 only to drop this voltage on the input of IC-8. Instead we will drop the current directly through the R179 - TP-18 series, and ordinarily we would want to develop a 10 mV level at the input of the CA3080. However, here we have to build the signal up to 20 mV because we have two 3db losses in the filter to come.

We could with some effort calculate the current out of the sine shaper CA3080, IC-7, but instead we will just use information from the shapers in the previous options. We know that this current output through 39k gives a 5 volt level (See IC-8 and IC-9 of Option 2 for example). Thus, the current out must be 5/39k = 0.128 ma at the peak of the sine waves. We want to choose a resistor R such that 0.128 ma developes a voltage drop of 20 mV. Thus:

$$R = 0.02/0.000128 = 156 \text{ ohms}$$

Allowing for component tolerances and the approximate nature of our calculations we will find it easiest to just put in a trim pot to set the exact amplitude. Thus, instead of the 156 ohm resistor, we use a 82 ohm resistor in series with a 100 ohm trimmer. While 20 mV at the input of a CA3080 is more than we generally want for linearity, here we still have the two filters to help us out, and after all, we have just put the signal through a CA3080 stage (IC-7) with 78 mV at the input with the specific intention of rounding. Our setup gave us an excellent sinewave from 30 Hz to 30 kHz.

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