Due to very bad original I decided to split up the article into three pieces, text, figures and schematic, mostly because I was unable to scan the schematic part fully satisfying.

But have no fear, I put all the stuff back into a pdf-format.

Well here it is:

BUILD a NEW music synthesizer module

You asked for it! An add-on module to provide sine-wave output and a pulse generator with a

voltage-variable duty cycle.

by JOHN S. Simonton, JR.

When we first started running the Synthesizer back a few months ago (see References), we asked for reader comments and suggestions, more to see if anyone was listening than anything else. A number of people were listening and were kind enough to write with suggestions for new modules, some of which will appear in later parts of this series.

This month we´ll take a look at a module that will strengthen what some people considered a weak point in the original design of the VCO-lack of a sinewave output-and at the same time, add a useful capability that isn´t even available on most of the high-priced commercial gear:a pulse output with a voltage controllable duty factor.

At the heart of the Sine Converter/Pulse Width Modulator is one of the new quad current differencing National Semiconductor amplilier IC packages. These amplifiers have been pretty throughly covered in the technical and hobby press, over the last few months, so we won´t go into the operating principle of the IC. We´ll simply treat it as a little chunk of plastic that contains four relatively high-gain amplifier blocks.

When a triangular waveform is applied to the input of the module, it is buffered and amplifiedby the first of the gain blocks in the package before being applied to the PWM (pulse-width modulator) and sine shaping circuitry. The trimmer in the input of this first stage (R32, Fig.1) allows the gain of the stage to be varied to compensate for level differences in the signal source.

The pulse-width modulator is essentially a summing comparator built around the second amplifier in the package. The current produced by the voltage appearing across R20-which is the triangular output of the first amplifier-is added to the sum of the currents produced by the control voltages that appear across R21, R22, and R23. The total current flow into the inverting input is compared to the reference current flowing into the non-inverting input through R25. As long as the reference current is greater than the total current flowing into the inverting input, the output of the amplifier stays high. Resistor values are selected so that the current into the inverting input exceeds the reference current for a small part of each cycle of the triangle input. This causes the output to switch low, thereby producing a very narrow pulse for zero control voltage. As the control voltages across R21, R22 and R23 begin to rise, the total current into the inverting input of the amplifier increases, causing progressively lower points on the triangle to switch the comparator. The net result is a pulse whose width is proportional to increases in control voltage.

As the comparator switches on and off, it, in turn, switches the third amplifier in the package which inverts the pulse and squares up the rise and fall times. The diodes D6 and D7 serve the dual purpose of clamping the outputs at about 1 volt, merely restricting the maximum rise and consequently lessening any slew rate problems as well as providing biasing current to the inverting inputs of the amplifiers at times that they otherwise be reverse-biased. (One of the little goodies that the manufacturers of these IC´s fail to mention in their literature is that if any of the inverting inputs are allowed to reverse -bias, it fouls up the biasing of the other amplifiers in the package and causes glitches to appear in other outputs.)

Except for biasing requirements peculiar to the Norton circuitry the sine shaper is a classic textbook non-lineur feedback type with diode break points in the feedhack loop of the amplifier. Here we approximate a sine-wave with a series of straight line segments as shown in Fig. 2. Assume for a moment that we begin watching the sine converter at a point in time when the triangular output of the first amplifier is ramping down from the mid-point of the waveform. At the mid-point of the waveform, all the diodes in the sine converter (D1-D5) are reversed-biased so that the only element in the feedback loop is R17. This resistor alone determines the gain of the stage and consequently the rate at which the output voltage of the amplifier increases. This corresponds to line segment 1 in Fig. 2.

Eventually the output voltage reaches the point at which it is greater than the voltage at the junction of the voltage divider consisting of R6 and R7. At this point, diode D1 forward-biases and parallels R7 with R17, resulting in in lower gain and a new line segment (segment 2). As the output voltage increases further, it eventually reaches the point at which D2 is forward-biased, thereby paralleling R5 with R7 and R17 and resulting in line segment 3. Finally, D3 forward-biases, adding R3 to the parallel network resulting in the smallest sloped segment, 4. The end of segment 4 corresponds to the highest point on the input waveform.

On the way back down, the diodes are progressively reverse-biased, resulting in the reverse sequence of line segments. As the signal passes through the mid-point and heads lower, D4 and D5 sequentially forward-bias, resulting in line segments 5 and 6 respectively. Ordinarily there would be a seventh breakpoint, but since the bottom corner of the triangle produced by our VCO is rounded anyway, it is unnecessary in this application.

Assembly

Even though all the active devices are contained in the single integrated circuit package, there is still a lot going on in this circuit and the external resistors and diodes required consume some space. If you´re not following our modular construction technique, any method of construction may be used. In the prototype, a standard single width module (2 x 4,5-inch panel) was indicated by the input and output jacks, but to fit all of the parts behind this relatively small panel, it was necessary to place the diode breakpoint components on a small auxiliary circuit board mounted above the main board.

Except for the double circuit board approach, assembly is the same as with any other project. Boards may be etched at home, using the full-size patterns shown in Fig. 3, or are available commercially. Parts placement is shown in Fig. 4. Notice in particular that input resistor R12 is not mounted on the circuit board, but rather connects between point H on the board and the hot side of the input jack (J1) on the front panel.

Watch your soldering temperatures on the IC and all the diodes: as with any semiconductor, overtemping can knock them out. When installing the IC, also be particularly careful about the orientation of the package þþs itþs installed. Putting this device in the circuit backwards will reverse the power connections to the package and will most likely result in smoke the first time the power is applied.

When all the circuit board wiring is complete, solder in place wires long enough to reach from the various input and output points on the board to the front panel connections before proceeding with mechanical assembly. The smaller hoard is mounted above the larger board with a 4-40 bolt and 7/8-inch spacer. When wiring these two boards together, you will be better off routing the four wires over the rear edge of the smaller board and then across the larger board to the proper connection points, as indicated in Fig. 5. With all the wiring going over one edge, servicing is simply a matter of ”folding” the board off; but with wires going over two edges, the smaller board becomes captive and can´t be removed without unsoldering.

The front panel can be made from any convenient material (chrome-plated steel with screen printed designations in the prototype) and is fastened to the circuit board with small ”L” brackets and 4-40 hardware.

Testing and calibration

If an oscilloscope is available, you can use it to take a look at the various waveforms as testing and calibration progresses, but it’s not necessary. The only equipment you really need is a VOM. the VCO that you’re going to use the module with, and an amplifier.

Connect a power source to the connections on the rear edge of the circuit board; ”+ +” to + 18V and ground to ground. The synthesizer power supply described in an earlier article is, of course, designed for this, but any power source, including a couple of 9-volt batteries, will do. Jumper the output of the triangle source to the input jack of the module and jumper the pulse output to the high (line) level input of a hi-fi or musical instrument amplifier.

Turn on the power and, this first time out, allow a couple of minutes to stabilize voltages, re-form any electro-lytics that may have been stored for some time. Ground one of the Sine/PWMs module´s control voltage inputs by connecting it to the 0 to 5-v bias supply pin jack on the synthesizer power supply and turning the bias source control knob fully counterclockwise. The second bias source on the power supply can be used to apply a constant voltage to the VCO corresponding to about middle C (l.25V for a properiy calibrated VCO).

Turn the adjusting disk of the ”pulse” trimmer (R32) fully counterclockwise. There should be no sound from the module at this point. Slowly advance R32 until you first hear the familiar whine of a narrow pulse waveform, then stop.

Disconnect the amplifier from the pulse output of the module and re-connect it to the sinewave output. You should hear a tone atthis output, and as the ”sine” trimmer R33 is turned the timbre of the tone should change. Some point in the rotation of this trimmer should produce a tone that is noticeably more mellow than other settings.

If an oscilloscope is available, it can be used to confirm that this setting produces the best sinewave. Figures 6, 7 and 8 show oscilloscope traces corresponding to the sine trimmer being set too far counterclockwise, too far clockwise, and correctly.

Setting the sinewave symmetry may have caused the pulse output to change slightly, so once again connect the pulse output jack to the input of the amplifier. Rotate the”pulse” trimmer R32 counter clockwise until the pulse output stopp (if it hasn’t already), then advance the control until the pulse can once again just be heard.

Increase the control voltage slowly to about 5, and observe that as the control voltage increases, the sound becomes proressively more ”full”. A scope may he used to verify that increasing control voltages increase the width of the pulse and that the duty factor of the pulse reaches 50% (square wave) when the control voltage is at 5 (+/- 10%). Similarly, test the other two control voltage control inputs.

As a final test, return the control voltage to ground and listen to the pulse output as the frequency of the VCO is varied over its entire range. If at any frequency the sound of the pulse drops out, advance the ”pulse” trimmer slightly until the sound returns.

Operation

When using the Sine Converter/PWM module, simply think of it as part of the VCO **-** expanding the versatility of an already present waveform (pulse) and adding a waveform not previously available (sine).

After playing with this module for a while, you may come to feel that a sinewave is not one of the biggie waveforms in electronic music, but it is the only pure tone (if you want to look at it that way) and the sinewave is the basic building block of all sounds. The problem, more than anything, is that it´s too basic. Only a couple of natural instruments come even close to producing a sinusoid. The flute is one, and Fig. 9 shows a connection using our synthesizer to produce a flute sound. Attack and decay times of the function generator should be set moderately short to properly simulate the envelope of a natural instrument. Using the controller step output to trigger the function generator provides for sustain as long as a key is held down. Bass, conga, bongo, tom-tom; any drum that doesn’t have provisions for snare produces a damped sinusoid.

By using the same connection that produced the flute, we can also produce drum sounds. The difference will be in the function generator; for drum sounds, we need the shortest possible attack and a moderate decay. Whereas the step output of the controller was used for the flute, the proper trigger for drums will be the pulse.

Pulse

There’s certainly nothing basic about a rectangular pulse train, and a rectangular pulse train with varying duty factor is about as far from being basic as a synthesizer is from a nose flute. Probably the first thing you learned after you got through building one-transistor radios was that a square wave contains only odd-order harmonics. You may have even learned that the harmonic structure of a square wave is such that the relative amplitude of any given harmonic is the reciprocal of its order numher-the third harmonic is 1/3 the magnitude of the fundamental, the fifth is 1/5, seventh is 1/7, and so on. Then, like the rest of us, you probably got in the sloppy habit of calling any repeating rectangular pulse train a square wave, and from there you really got fouled up by thinking that any rectangular pulse train contains only odd harmnnics. Not so. First of all, as the duty factor of a rectangular pulse train decreases below 50%, it no longer contains only odd harmonics. In fact, a string of rectangular pulses with a duty factor of 25% (1/4) has a null in its spectrum at the fourth harmonic and all integral multiples of the fourth harmonic (8^{th}, 12^{th}, 16^{th}, etc.). A 20% (1/5) duty factor rectangular pulse train nulls at the fifth harmonic and all integral multiples of the fifth harmonic. Similarly, a 1/10 duty factor nulls at the 10th harmonic and a 1/100 doesn´t null till the 100^{th} harmonic.

While all of these interesting things are happening to the nulled harmonics, an equally interesting thing is happening to the relative amplitudes of the harmonics that are present-they´re flattening out. Whereas the first three harmonics of a 25% duty factor rectangular waveform have relative amplitudes of 1.0, 0.7l and 0.33 respectively; the first three harmonics of a 10% duty factor rectangular pulse train are 1.0, 0.9 and 0.87. For the folks that find joy in such things, the first ten harmonics of a variety of selected duty factor rectangular pulse trains are listed in Table 1. This list doesn’t prove a whole lot, but it was prepared by a computer, so it must be worth something.

What we have shown, though, is that whiIe the square wave is generally considered to be a harmonic-rich waveform, a simple thing like reducing its duty factor makes it richer still. This is a handy thing to rememher when you're working with bandpass filters, and it's naturally the reason that a filter swept over a narrow pulse produces a much more striking sound than sweeping a broad pulse.

You're probably going to get very excited the first time you use an arrangement such as that in Fig. 10 to cyclicly vary the duty factor of the pulse. This connection produces a very distinctive "phasing" type sound. The reason for this is more mathematical than would be interesting here, but qualitatively it has to do with there being two sinewaves going in and out of phase for each harmonic. If the two sines are exactly in phase, the harmonic is at maximum, and if they´re out of phase, the harmonic nulls. As we said, you really have to see the math to believe it-unless, of course, you´re listening to it.

One more point really needs to be mentioned before you´re turned loose on your own. You will notice that in all these discussions about pulse duty factors, never once have we gone above 50%. That's because there is reciprocity of duty factors that are equal increments above and below 50%. In other words, a 40% duty factor sounds the same as 60% ; 25% the same as 75%, and so on. This is the reason that the duty factor for our maximum system standard control voltage of 5 volts is 50% rather than 100% . If for some reason you decide that you absolutely must have 100% duty factor for a 5-volt control input, you can always apply the 5 volts to two of the control voltage input jacks at the same time. Don't forget the implicit power of control voltage summation.

As a final demonstration of both reciprocity of duty factors and control voltage summation, let´s suppose that you´re designing a sound that requires the duty factor of the pulse to decrease as the control function to one of the other modules (VCA would be common) is increasing. Your first impulse might be to use some form of inverter to change the positive-going control voltage to a negative-going one. That´s one way, but a better way would be to save the inverter for a place where you really need it and simply put a constant 5 volts into one of the PWM control voltage inputs while applying the function to one of the other control inputs.

Here youre starting with a duty factor of 50% and increasing it close to 100% as the function increases. Since your ear is unable to tell whether a duty factor is increasing or decreasing from 50%, the effect is the same as starting with a broad pulse and going to a narrow one.

Parts list

C1 - 10 uF, 15 V electrolytic

C2, C3, C4, C6, C7 - 2,2 uF, 10V electrolytic

C5 - 100 uF, 15V electrolytic

D1-D7 - 1N914

IC1 - LM3900 quad current dif. amp.

R1 - 6k8
R2, R16, R18, R25 - 10k
R3 - 47k
R4, R12 - 39k
R5, R9, R15 - 150k
R6 - 330k
R7, R8, R11, R13, R14 - 680k
R10 - 1M8
R17 - 220k
R19 - 680R
R20 - 27k
R21, R22, R23 - 33k
R24 - 56k
R26 - 330R
R27, R28 - 1k
R29 - 270R
R30, R31 - 2k2
R32 50k trimmer pot
R33-10k trimmer pot

References, Electronic Music Synthesizer

Part I - Build a Modular Electronic Synthesizer. May, 1973 p. 38
Part II - Build the Control Electronics. June, 1973 p. 56
Part III - Details of Keyboard Construction. July. 1973, p. 46
Part IV - More Synthesizer Modules. Sept. 1973, p. 53
Using the Synthesizer. Oct. 1973, p. 60

R-E

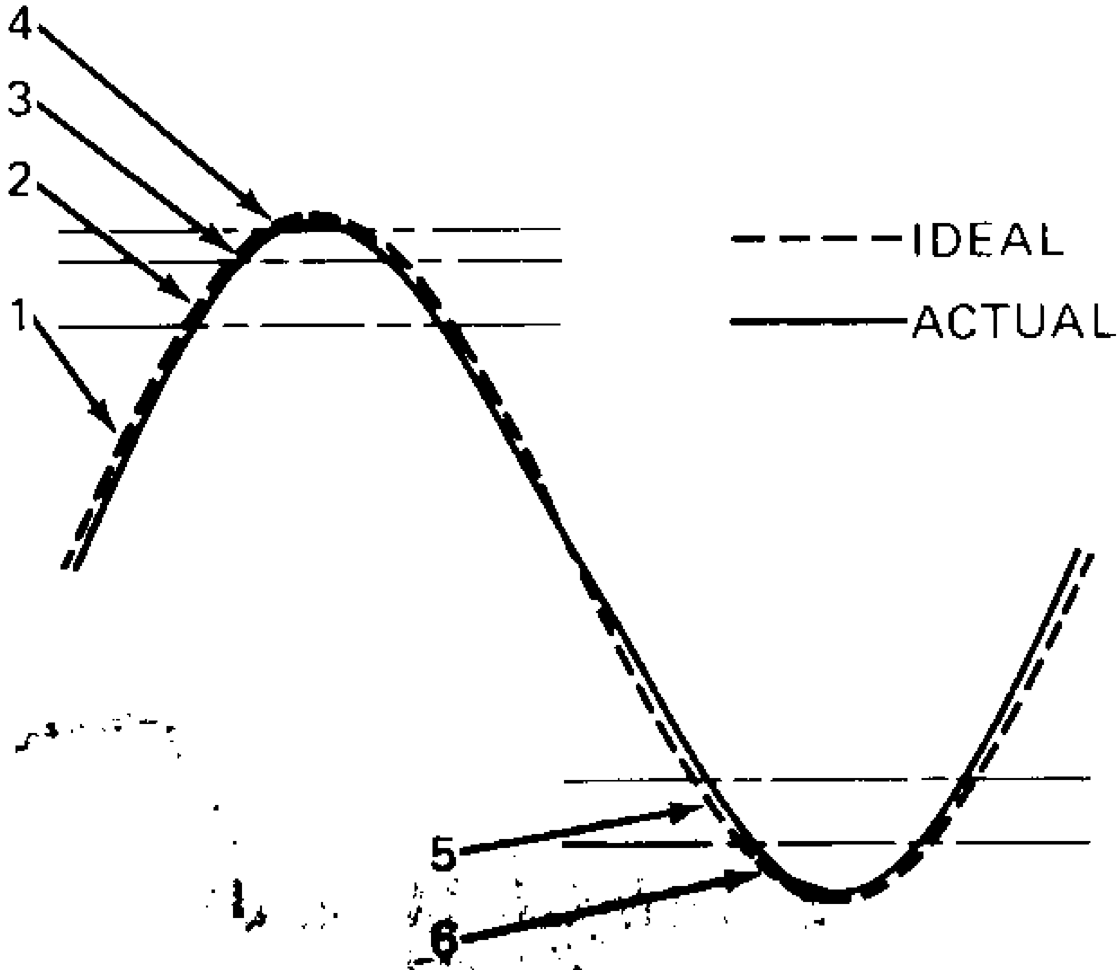


FIG. 2—SINEWAVE APPROXIMATION.

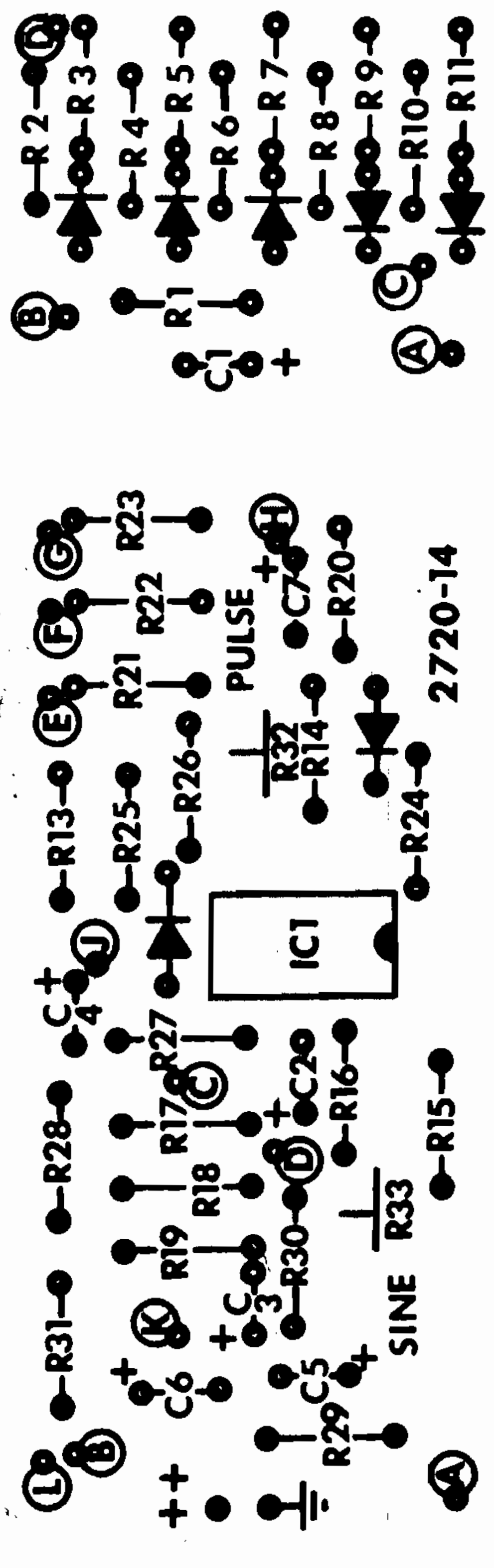


FIG. 3 (left)—FULL-SIZE PATTERNS for the triangle/sinewave converter and variable pulse-width modulator. Keep all parts on one board if you have the room behind your panel. Otherwise, cut the board as indicated. FIG. 4 (right)—HOW PARTS ARE POSITIONED on boards.

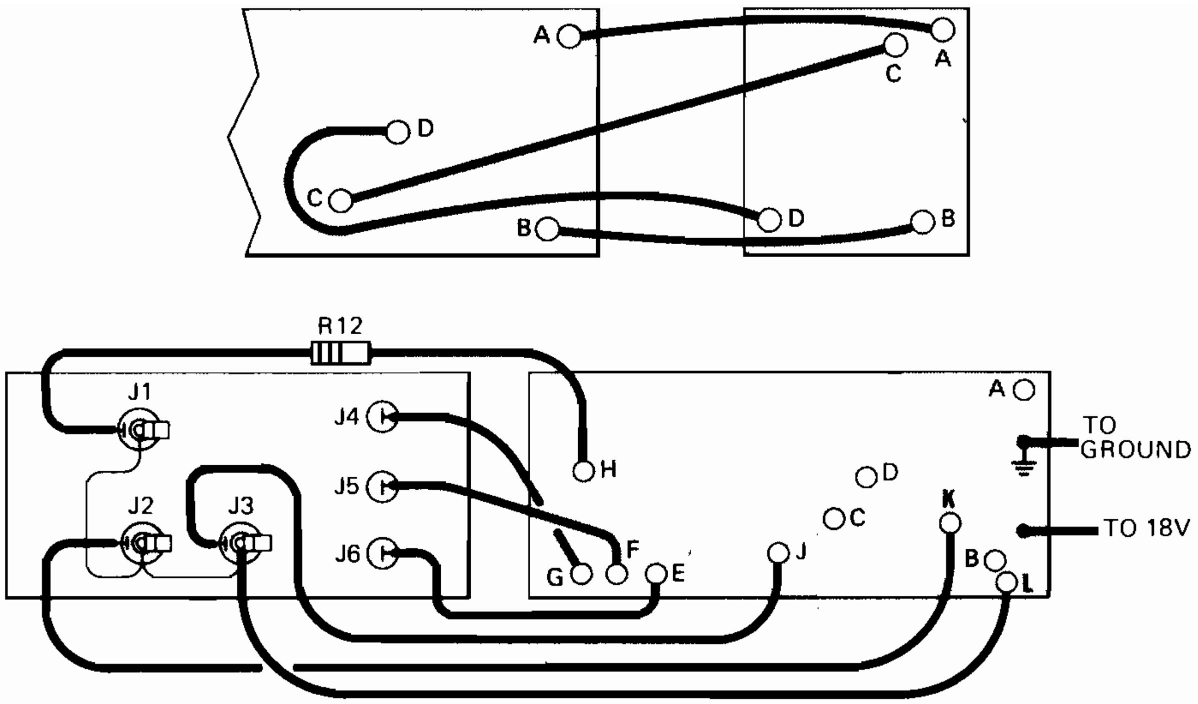


FIG. 5—THE CONNECTIONS BETWEEN main and auxiliary boards, and to front panel.

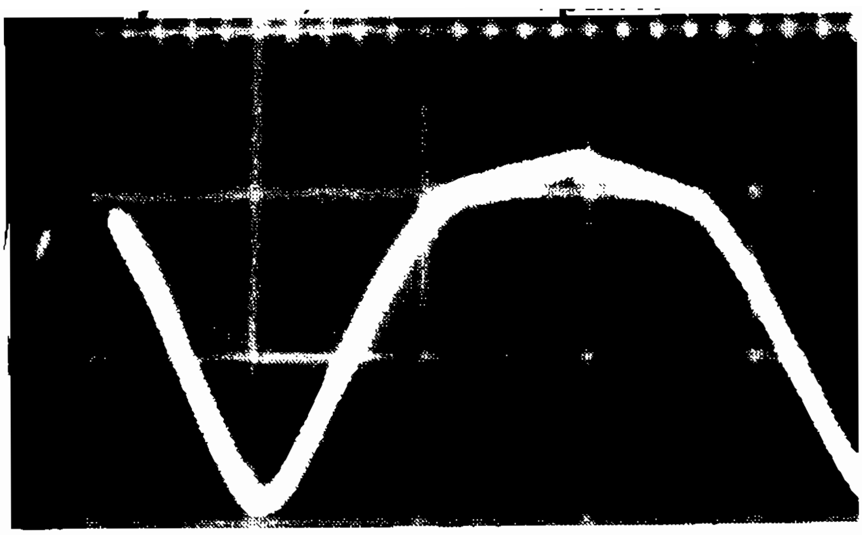


FIG. 6—TRIMMER TOO FAR CLOCKWISE.

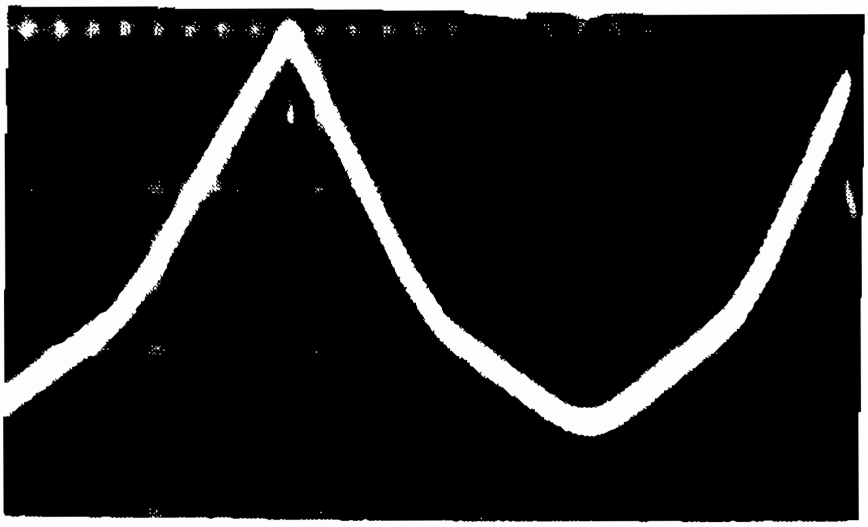


FIG. 7—NOT FAR ENOUGH CLOCKWISE.

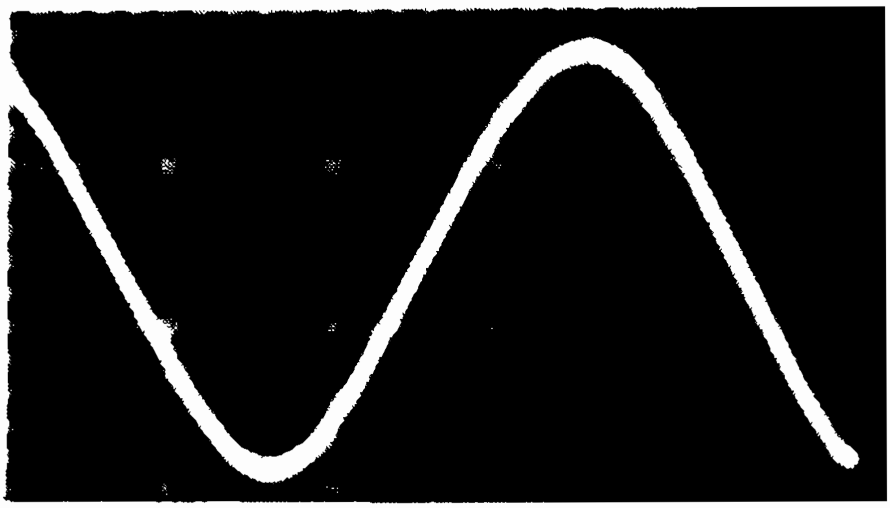
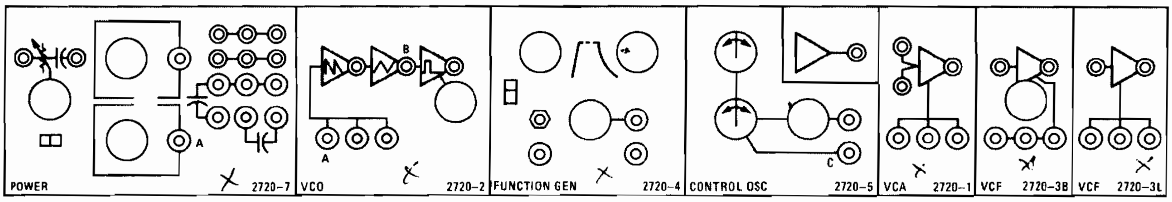


FIG. 8—CORRECT TRIMMER SETTING.



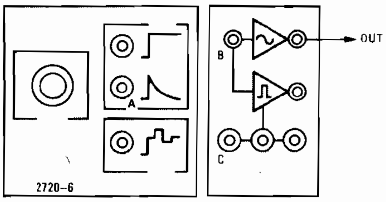


FIG. 9—CONNECTING THE SYNTHESIZER TO PRODUCE A FLUTE SOUND.
By changing the attack and decay times, drum sounds can also be produced.

plitude of any given harmonic is the reciprocal of its order number—the third harmonic is 1/3 the magnitude of the fundamental, the fifth is 1/5, seventh is 1/7, and so on. Then, like the rest of us, you probably got in the sloppy habit of calling any repeating rectangular pulse train a square wave, and from there you really got fouled up by thinking that any rectangular pulse train contains only odd harmonics. Not so.

First of all, as the duty factor of a rectangular pulse train decreases below 50%, it no

TABLE 1

d.f. / harm.	50%	33%	25%	20%	10%
fund.	1	1	1	1	1
2nd	—	.5	.71	.81	.95
3rd	−.33	—	.33	.54	.87
4th	—	−.25	—	.25	.77
5th	.20	−.20	−.20	—	.65
6th	—	—	−.24	−.17	.51
7th	−.14	.14	−.14	−.23	.37
8th	—	.12	—	−.20	.24
9th	.11	—	.11	−.11	.11
10th	—	−.10	.14	—	—

Harmonic amplitude for selected duty factor pulses.

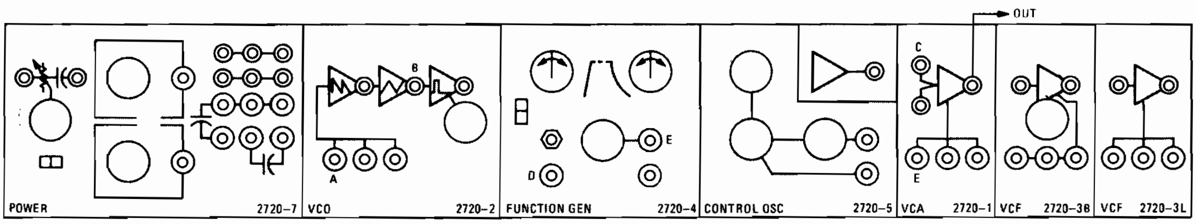
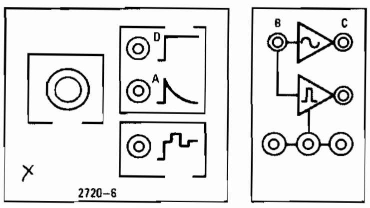
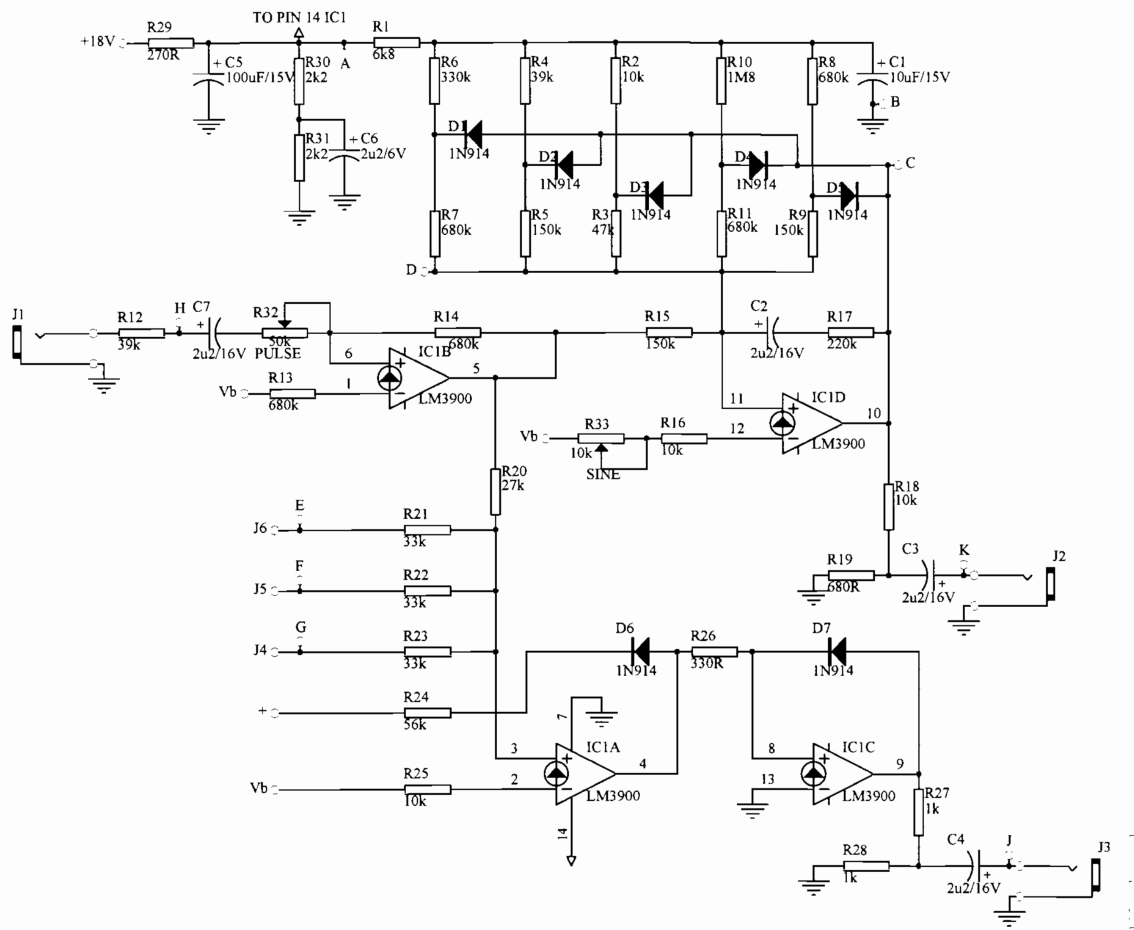


FIG. 10—CONNECTIONS FOR CHANGING PULSE DUTY FACTOR CYCLICLY.





Title		
SCHEMATIC OF THE SINE CONVERTER - PULSE WIDTH MODULATOR		
Size	Number	Revision
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Date: 18-Nov-1997		Sheet of
File: E:\CLIENT\PROJEKT\FIG1.SCH		Drawn By: