ELECTRONOTES 87

NEWSLETTER OF THE MUSICAL ENGINEERING GROUP

1 PHEASANT LANE

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GROUP ANNOUNCEMENTS:

CONTENTS OF EN#87

We are starting in this issue the first or a series on "animation" devices or enricnment devices for synthesized sounds.   This time we are discussing a multi-phase and summing unit.   Later we will be looking at filter banks, high-ripple filters, tone wheels, and perhaps other devices.   We welcome any comments or additional contributions. Dave Rossum gives us the setup of the Solid State Music synthesizer IC line beginning on page 11. We also have a circuit for a longer delay line chip, and a guitar pickup design for the home builder.

Two new supplements and the first of our collections of "preferred circuits" are being offered with this issue, and ordering information for these is on the mailing sheet with this issue.   Supplement S-017 is a set of 10 "literature evaluations" of some "classic" papers. Supplement S-016 is the "Laboratory Problems and Examples in Active, Voltage-Controlled, and Delay Line Networks" that we mentioned some time ago. This is a "do as you learn" type of lab guide that could be used as a college lab guide or as a guide for the individual experimenter at home.   There are also enough examples given that the manual can just be read without doing any of the suggested experiments. This should serve to bring together many of the ideas a reader may have about filters. There is no advanced mathematics in the manual. There is only one integral and one differential, both of which are not essential, and the rest is mostly algebra and words and graphs.   The 60 or so pages of text are organized into eight chapters and six experiments as follows:

Chapter 1	Ideal Op-Amps and Basic Op-Amp Circuits
Chapter 2	Initial Experiments with Real Op-Amps
	Expt. 1 Op-Amp Bandwidth
	Expt. 2 Op-Amp Slew Rate
Chapter 3	S-Plane Analysis Techniques and Active Filters

News And Notes:

"The Craig Anderton Music Tape" is a cassette recording of music by Craig Anderton, and is available through PAIA Electronics, 1020 West Wilshire Blvd., Oklahoma City, OK 73116 at a cost of $5.95 + 50¢ postage.   Readers who have followed Craig's reviews in EN may want to take the opportunity to do a personal review of the reviewer.

The New England Conservatory of Music will hold a Summer School from June 26 - August 4, 1978 featuring workshops, courses and master classes. A highlight of special interest to our readers will be the Electronic Music Workshop, June 26 - June 30 with Robert Ceely and the Electronic Music in the Classroom Workshop, July 10 - July 14, with Larry Allen. For more information, contact the N.E.C. at 290 Huntington Ave., Boston, MA 02115 (617)-262-1120.

John Cage and David Tudor will perform a benefit concert for PASS, the Public Access Synthesizer Studio, Monday, April 10, 1978 at 8 PM in the Eisner and Lubin Auditorium of NYU's Loeb Student Center. Tickets are available at the Loeb Ticket Booth, 566 LaGuardia Place, New York, NY 10012 (212)-598-2027. For information on PASS itself, write to PASS, 135 W. Broadway, New York, NY 10013 (212)-964-9891.

The Boston School of Electronic Music has relocated to 28 Highgate St., Allston, MA 02134 (617)-782-9100.

A position is vacent at the School of Music, University of Iowa, Iowa City, IA 52242.   The position is "Audio Specialist/Electronics Technician", and involves recording duties as well as circuit design and involvement with the multi-color laser/music system at the university. For more information, contact Prof. Lowell Cross at the School of Music (319)-252-5976. [Electronotes has forwarded resumes from our files to the school, but those we have on file may want to inquire directly.]

STAR Instruments, PO Box 71, Stafford Springs, CT 06076 has two new "SYNARES". The SYNARE 2 has a microprocessor based system to scan a playing surface, store and play sequences, and so on. The list price is $1395. The SYNARE 3, with a dynamic playing surface is battery operated at a price of $195. Write STAR for more info.

A line of small computer equipment is available from Omicron Systems, PO Box 588, Lewiston, ME 04240.

Reader's Questions:

▶ Q: You reference a magazine American Scientist, which I have just discovered is not a misprint of Scientific American. Where can I get the right one?

A: American Scientist, 345 Whitney Ave., New Haven, CT 06511 is the address.

A Sawtooth-Driven Multi-Phase Waveform Animator:

The Synthesis Of "Animated" Sounds – Part 1:

-by Bernie Hutchins

INTRODUCTION TO THE SERIES: This is the first in a series of three and probably four reports that will describe methods and devices for producing what we can call "animated" sounds.   By this, we mean methods of starting with the more or less "static" waveforms and adding to them additional shorter term fine structures that make the waveform already more interesting to the ear before standard types of processing are added. This series will thus be part of the attack on the problem which has been with us for a long time: how do we make sounds less "electronic" and more "natural"?

INTRODUCTION TO THIS FIRST PART: Here we will be describing what many people might call a "fat sound" processor.   We know that a "fatter" sound or richer sound is produced when we run multiple VCO's in parallel, all at the same nominal frequency, and let the small variations cause a shifting or beating effect.   The main drawback to this is obviously that you need several VCO's to produce a single voice.   Here we propose to keep the basic result of shifting phases in the output, but drive the unit with only one VCO.   The animator to be described is basically an in/out device, although it is easy to see that a full panel of controls could be added if a user wants to experiment further.   The unit takes in a single sawtooth waveform, and then uses eight sawtooth phase shifters to provide shifts from zero to 360°. These shifts are voltage-controlled, each by an independent oscillator which operates on a frequency of about 0.01 Hz to 1.0 Hz.   The eight shifted sawtooth waveforms are then mixed back together, along with the original, to form a composite sound.   It is obvious that if we wish we can easily follow each of the shifted sawtooth waveforms with a saw-to-triangle converter, followed by a triangle-to-sine converter, so that phase shifted mixtures of triangles and sines can be achieved.   However, here we will rely on filtering, and on the fact that the device does respond to waveforms other than the sawtooth (in some manner, not necessarily as a phase shifter), to produce a variety of output sounds.

THEORY OF CIRCUIT OPERATION

The sawtooth phase shifter is a simple modification of the multi-phase unit described in our Application Note AN-73. The only modification made here is done so that the input sawtooth ranges from -5 to +5 instead of the 0 to +5 in the application note. Likewise, the output sawtooth ranges from -5 to +5. The circuit is shown in Fig. 1. While three op-amps are shown in Fig. 1, the top op-amp is just an inverter, and can be used in common for all eight shifter sections. Thus, each additional shifter section will require only two op-amps (plus two additional op-amps for the control oscillator to be described).

The phase shift circuit consists of a comparator and a summer. When the input sawtooth exceeds the control voltage V_c, the comparator goes high, producing a -10 volt change at the output of the summer. This provides the phase shift in the sum of
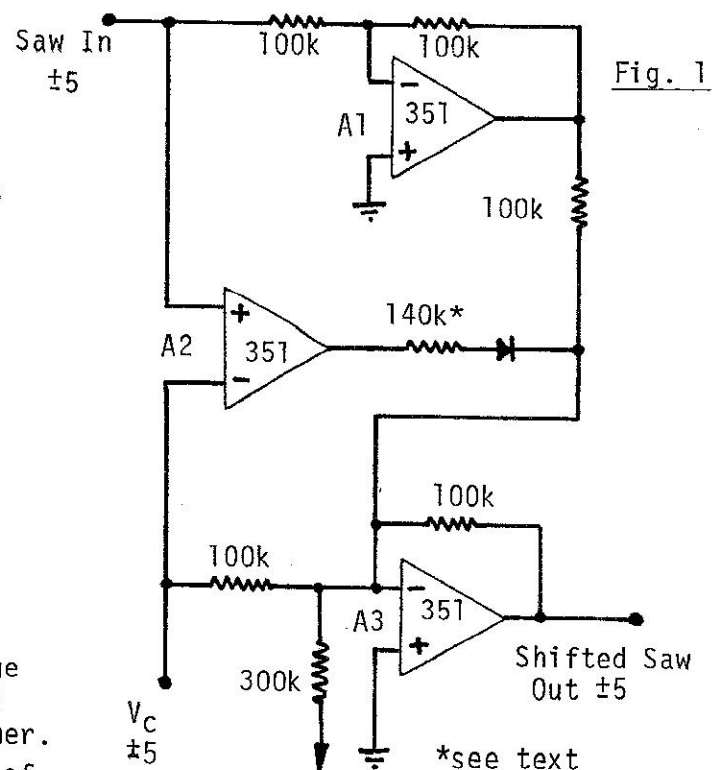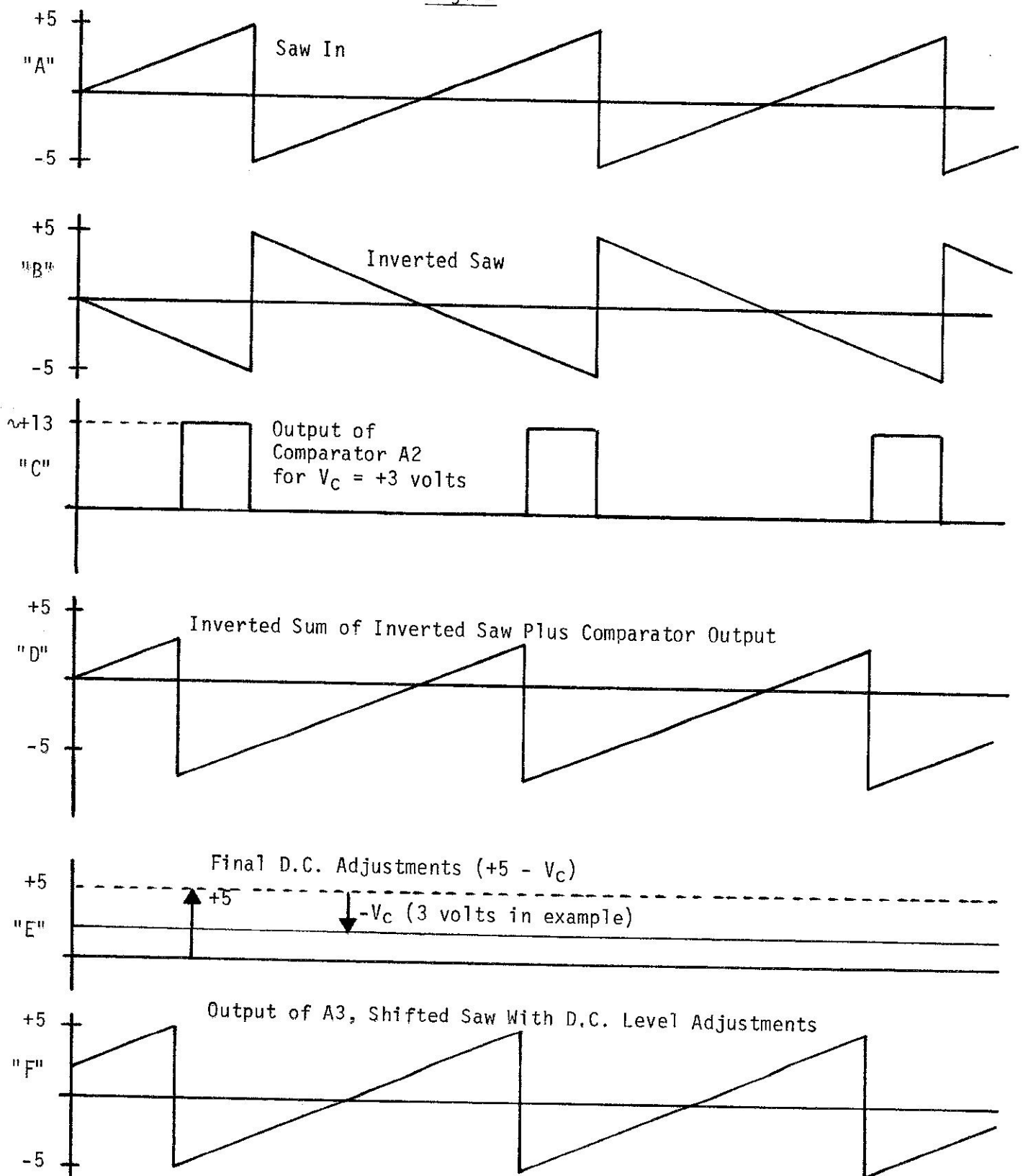

Fig. 1

Fig. 2

"A" +5 / -5 — Saw In

"B" +5 / -5 — Inverted Saw

"C" ∿+13 — Output of Comparator A2 for V_C = +3 volts

"D" +5 / -5 — Inverted Sum of Inverted Saw Plus Comparator Output

"E" +5 — Final D.C. Adjustments (+5 - V_C)
+5
-V_C (3 volts in example)

"F" +5 / -5 — Output of A3, Shifted Saw With D.C. Level Adjustments

the comparator output and the inverted sawtooth. The remainder of the circuitry is concerned with restoring the correct (zero) D.C. level to the output. Study of the waveforms of Fig. 2 will show how the shifter works. Waveform "A" is the input saw while "B" is the inverted saw. As an example, we assume V_C = +3 volts, so the input saw causes the comparator to go high when the sawtooth exceeds +3 volts, producing the output shown in waveform "C" (allowing for the fact that the op-amp does not reach its full supply voltage, and the series diode). The inverted saw and the comparator output

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are summed in A3. The resistor shown as 140k (I used 100k in series with 39k) was chosen so that there was no discontinuity in the waveform at the point where the inverted sawtooth resets high while the comparator goes low. If you use an op-amp other than the 351, you may have to adjust this resistor slightly. However, the final "mix" at the output of this module is quite complex, and small ramp imperfections may not matter at all, so perhaps standard value 130k or 150k resistors will do. The sum at the output that is due to the inverted saw and the comparator is shown in waveform "D". Note that this is a phase shifted saw.

It remains to restore the D.C. level, since the level in "D" is -2 volts. This is done by adding +5 volts (that is, -15 volts through 300k to the inverting summer A3), and subtracting V_C = +3. This adjustment is shown in waveform "F" of Fig. 2. The D.C. adjusted output is shown in waveform "F" of Fig. 2.

CHOOSING A CONTROL OSCILLATOR

Since we will need eight independent control oscillators, we have to choose a simple design. The standard "triangle-square" oscillator formed from the loop of an integrator and a Schmitt trigger is an obvious choice, and we will use it after making one simple modification. This modification is needed because we want to work at very low frequencies. Fortunately, low bias current op-amps are available so there is no real problem reaching low-frequencies. However, to save space, we would like to keep our capacitors at about 0.1 mfd. This means that the resistors in the integrators may run to several hundreds of megohms and even higher, and these resistors are hard to obtain. Since we prefer to use resistors below 22 megohms, the upper limit of the carbon resistors generally available, we use a two stage approach, placing an attenuator before the integrator resistor. The circuit is shown in Fig. 3.

Fig. 3
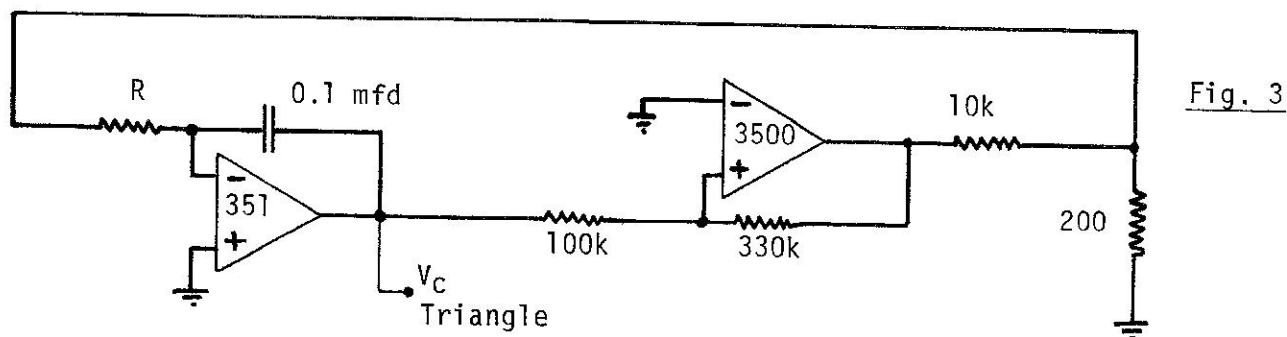
We can determine the frequency of oscillation by simply multiplying the standard formula (see derivation in AN-67) by the attenuating factor. This uses the fact that the 200 ohm resistor is much smaller than 10k, and assumes that R is 100k or greater. The formula for Fig. 3 is:
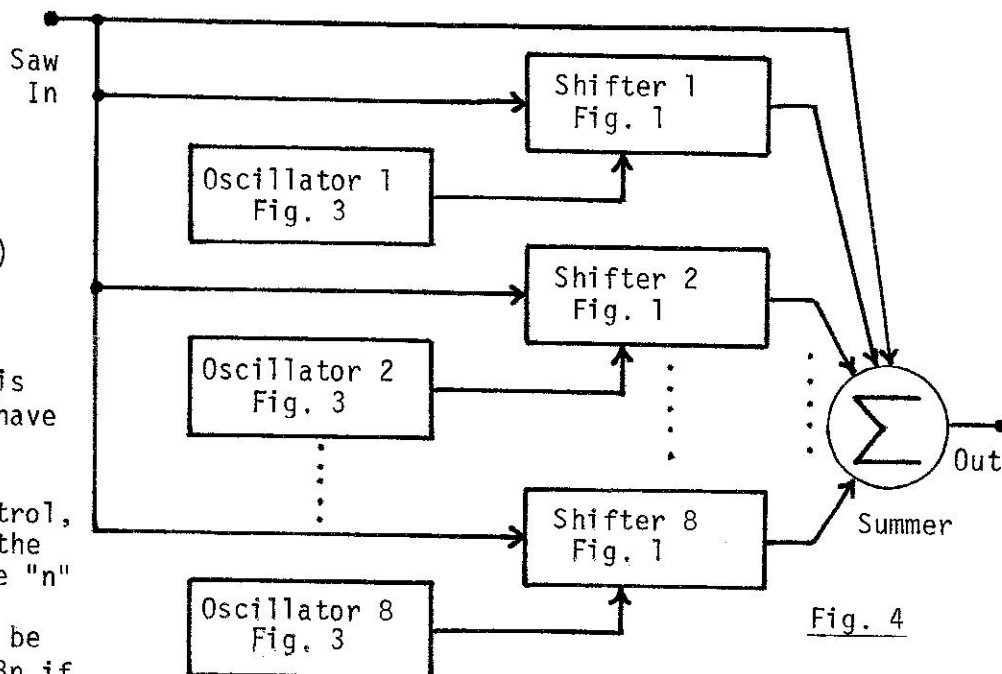
$$f = 1.62 \times 10^5 / R$$

Thus, a 22 meg resistor for R will get us below 0.01 Hz. The benefits of the circuit of Fig. 3 are that we can use physically smaller capacitors (and avoid electrolytics and the associated polarity problems), and we can use standard resistors. The disadvantages are that two more resistors are required, and some waveform symmetry may be lost. This symmetry may be lost because the voltage on the 200 ohm resistor is only of magnitude of about 270 mV, so an offset voltage at the input of the 351 will cause waveform asymmetry. This would not seem a problem in this application, but is pointed out so that it is clear that the attenuation process should not be considered as one which can be extended indefinitely to use smaller and smaller capacitors. The op-amp marked 3500 could be just about any op-amp you have on hand, a 741, 307, 3500, 351, or whatever. The amplitude of the triangle is a little over 4 volts with the 100k and 330k resistors shown. These were chosen so that the control signal is well within the ±5 volt control limits of the shifter. If you wish to push the limits closer, use 300k instead of 330k and use 1.47×10^5 in the frequency formula.

PRESET PARAMETERS

We have now determined that it is possible to phase shift a sawtooth waveform under the control of a control voltage (Fig. 1) and that a simple oscillator (Fig. 3) can be used to supply this control voltage. This is the easy part. We now have to choose the number of shifters, the operating frequencies of each control, and the proportions in the final mix. If we choose "n" stages, this gives 2n operating parameters to be set. This would go to 3n if we allowed the depth of each shift to be varied, and to 4n if we allowed the initial phase to be selected. Our experience with such multiple parameter systems suggests that we will have to choose most of these as presets, and be satisfied with our choice. If we allow too many variables, we have too many controls in proportion to the variety of sounds that can be produced. We thus will think of our animator as consisting of the circuits shown in block form in Fig. 4. We choose eight shifter sections, and eight control oscillators. Eight seems to be a satisfactory number because listening tests indicated that if one watched the control oscillator waveform with a scope (remember, these are slow waveforms of 0.01 to 1 Hz), and listened to the total mix, no correlation of control level and sound content was evident. We also choose the mix to be a sum of all shifter outputs and the original, all weighted equally. We will allow for the idea that several different summers and different output jacks may be employed. The biggest design choice however is presented by the choice of control frequencies, and we will discuss this problem separately in a moment. Here we will simply note that it is possible to "program" these frequencies with only 8 resistors (the R resistors from Fig. 3), so if we use a 16 pin DIP IC socket for example, we can plug in different resistors and experiment before finally closing the cover of the module.

Fig. 4

SELECTION OF OPERATING CONTROL FREQUENCIES

In selecting the operating frequencies for the control voltages, there are few guides that we can use. We have restricted the frequencies to 1 Hz or lower simply because this is an enrichment process of a tone with well defined pitch, and in this case, we do not want to produce significant "modulation sidebands" in the output. The only other guide we can employ is that we want to produce trends for the ear to follow but do not want the ear to pick up patterns in these trends. Thus, we want to be sure the control frequencies are not occuring at the ratios of small integers, otherwise the processing patterns will repeat and be detected. To a degree, we are well protected against repeating patterns by the fact that components used in the circuits have tolerances such that we could not get many small integer ratios except by careful trimming of values. So, as long as we do not make an effort, we will not get patterns. However, a selection process is available to us, and we might as well make use of it. This process is the method of selecting filter peaks for formant filters as discovered by Ralph Burhans (see EN#40). Ralph found that if you space frequencies at the fifth root of 2.1, you get no harmonic overlap over a 10 octave range. Thus we can develope a table of possible frequencies and corresponding resistor values, and from this table select eight that we actually want to use. This is shown in Table 1.

TABLE 1

FREQUENCY	RESISTOR (R)	ACTUAL R IN TEST	NOMINAL FREQ. (ACTUAL R)	MEASURED FREQ.
0.010	16.17 M	15M + 1.2M	0.00999	0.011 (+10%)
0.0116	13.95 M	-	-	-
0.0135	12.02 M	-	-	-
0.0156	10.36 M	-	-	-
0.0181	8.94 M	-	-	-
0.0210	7.70 M	-	-	-
0.0244	6.64 M	-	-	-
0.0283	5.72 M	-	-	-
0.0328	4.94 M	4.7M + 200k	0.0330	0.031 (-6%)
0.0380	4.25 M	-	-	-
0.0441	3.67 M	-	-	-
0.0512	3.16 M	-	-	-
0.0593	2.72 M	-	-	-
0.0688	2.35 M	-	-	-
0.0798	2.03 M	-	-	-
0.0926	1.75 M	1.6M + 150k	0.0924	0.089 (-4%)
0.1074	1.51 M	-	-	-
0.1246	1.30 M	-	-	-
0.1445	1.12 M	-	-	-
0.1677	0.965 M	-	-	-
0.1945	0.832 M	-	-	-
0.2256	0.717 M	680k + 36k	0.226	0.224 (-1%)
0.2617	0.618 M	560k + 62k	0.260	0.270 (+4%)
0.3035	0.533 M	-	-	-
0.3521	0.459 M	-	-	-
0.4084	0.396 M	-	-	-
0.4737	0.341 M	330k + 11k	0.474	0.510 (+8%)
0.5495	0.294 M	300k	0.539	0.530 (-2%)
0.6374	0.254 M	-	-	-
0.7393	0.219 M	-	-	-
0.8577	0.189 M	180k + 9.1k	0.855	0.920 (+8%)
0.9948	0.163 M	-	-	-

The last three columns of Table 1 give what can be considered here as an experimental verification of the frequency formula over the range of interest. The actual values are the frequencies which were used in the final design, and are very close to the first frequency set tried. The reader should realize however that any of the values shown can be tried, and that more than one can have the same value (knowing it will be spread by component tolerance).

TESTING OF DIFFERENT GROUPS OF CONTROL FREQUENCIES

To a first approximation, all combinations of control frequencies give the same basic sound at the output. The difference between the control frequency groups is in the time constants of the variations within the sound, and in a subjective feeling for patterns in these changes. The sounds are strongly pitched with a basic timbre that is somewhat like that of a sawtooth, but with a constant feeling of change, emphasizing different parts of the spectrum at different times. The sounds are richer, seem much more reverberant, and may remind you of the sound of an orchestra tuning up - a "drone" in which you hear different instruments coming in and out, changing the spectral composition. This change of spectral composition can be understood in terms of the cancelling or reinforcing of different spectral components of the sawtooth as the relative phases vary. Fig. 5 shows a simple example of the addition of four sawtooth waves that happen to fall 90° out of phase with each other. Note that the result is a sawtooth of four times the original frequency, indicating that the original first, second, and third harmonic have been cancelled out. Cases such as that in Fig. 5 do occur in the shifter output on a transitory basis. The total effect is somewhat like that which is heard when several nearly tracking VCO's are summed, but there is one advantage here. The tracking VCO's always seem to have a beat-like nature to their sum, probably because no more than three or four VCO's can generally be summoned for this job. In this animation module, there are eight units varying with well defined and controlled time constants, and this can be heard to be free of apparent patterns.

For an initial test of the system, a set of frequencies was selected that was the same as the measured values in Table 1, except frequencies at 0.2617 and 0.5495 in Table 1 were originally at 0.7393 and 0.9948. The original results were quite satisfactory, and the only reason for changing to the set in Table 1 was that a little less rapid time constant of animation was desired. That this could be achieved was discovered as a result of some special tests.

In one test, all the R resistors were set at 3.3M, setting all eight control frequencies at approximately 0.05 Hz. Setting all eight to such a low frequency is undesirable because the time constants of change are too slow. Also, when the power is first turned on, all eight oscillators start in phase, producing a sawtooth output, and it takes several minutes for things to get mixed up well. During this test, we shorted out one of the 3.3M resistors with first 330k and then 100k, shifting the frequency of one of the oscillators to above 0.5 Hz and then to well above 1 Hz. The result was that this one faster oscillator was enough to provide animation with a much faster time constant. However, it was possible to detect this oscillation by listening to the output, as one might expect. This is because the background provided by the other seven oscillators is little changed during any one cycle of the faster oscillator, so things can be heard to nearly repeat. Thus it can be understood how a gradual spacing of frequencies allows any one oscillator to "hide" in the changing background of the other seven.

In another extreme test, all eight oscillators were set with R at 150k, setting the frequencies at about 1 Hz. This was found to be satisfactory with regard to the amount of animation, but the time constants of change seemed a little fast, and the control voltage patterns were much too evident. Changing all R resistors to 330k produced the interesting change that the time constants seemed about right, and the patterns, while just detectable, were much less troublesome. Thus, if you are inclined to keep all shifting frequencies in a tight set, use a frequency of about 0.5 Hz. This choice is not too bad, although I tend to prefer the spread set of Table 1 myself. The close set (around 0.5 Hz) has a more harsh and "edgy" sound, but is a more constant sound, with exception made for the just detectable patterns. The spread set (Table 1) gives a less harsh sound, but one with more extremes in the result.

We could go on describing the results of different frequency sets and other parameter changes, but it gets more and more difficult to describe the sounds in words, so we will not attempt this. Probably the reader is either inclined to try this himself, or our description is enough for him as is.

Fig. 5
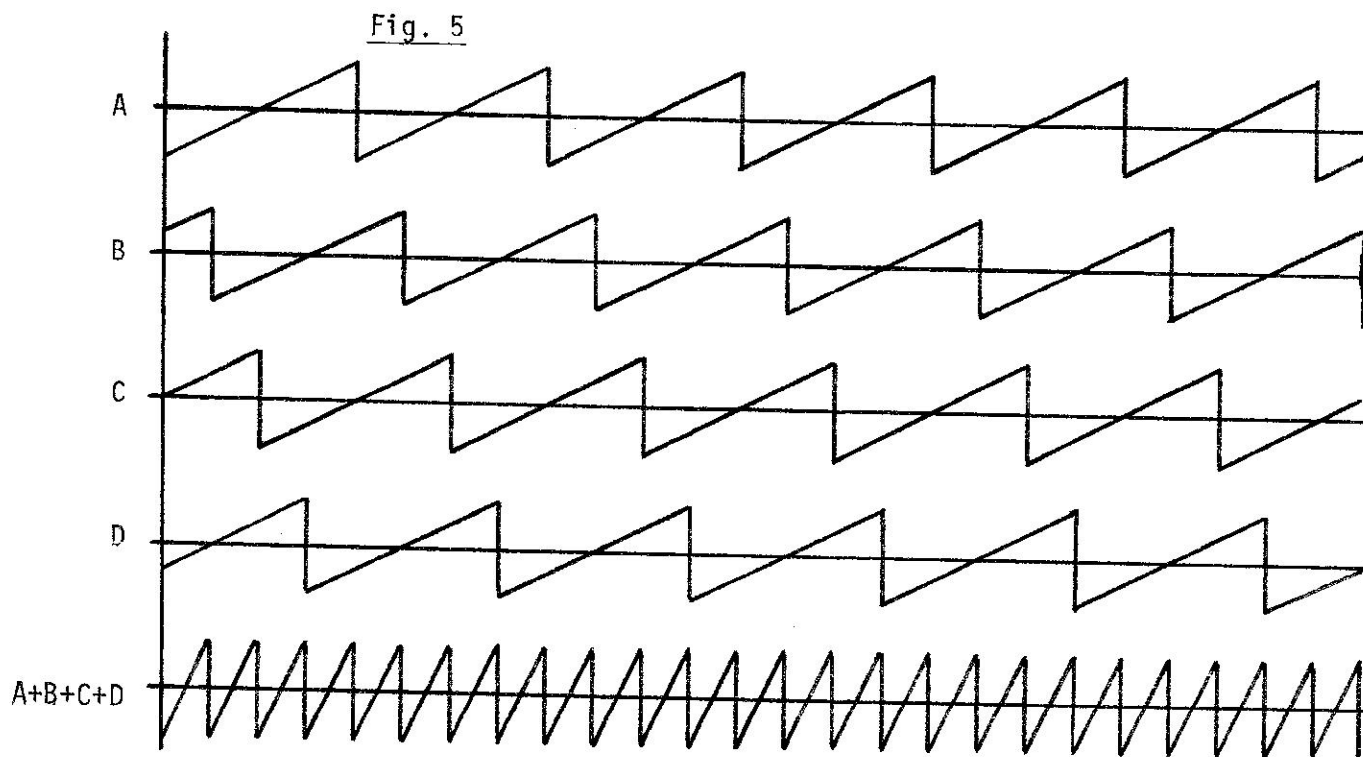
Before going on to a description of the full circuit, we want to make a few brief comments about the waveform at the output of the shifter. We would attempt to draw it except for the fact that it is very complex and constantly changing. If you have ever viewed the waveforms of live instruments, it is quite similar to them. Unlike the example of Fig. 5, which represents only one special case which would only exist for one transitory moment, the complete waveform is neither sawtooth or of constant amplitude. In fact, the peak amplitude varies by at least 2:1 from time to time.

## COMPLETE CIRCUIT DESCRIPTION

Probably many readers who have followed what we have presented so far know exactly how to build the animator module without any additional information. We should of course give one complete schematic to facilitate the construction phase of this project, and this is found in Fig. 6.

The full circuit of Fig. 6 uses 34 op-amps. Seven circuits identical to the first section within the dotted lines, except for the "R" value, are not shown in detail. You may want to add an input buffer to the circuit as well. The values shown as "R" may actually be the closest 5% value available, or you can use series combinations as in Table 1. We show only one summer, IC-34 which equally sums the original and the eight shifter sections. The gain of this summer was selected experimentally. In theory, the feedback resistor should be more like 100k, since at some time the total summed voltage should reach about +5 with this value. In practice, it is more useful to use a larger gain since the usual case is that the amplitude is much smaller than +5 volts due to cancellation of + and - sawtooth portions. If you should find in your experimenting that more than one summing combination is useful to you, just add a second summer. You may also find it useful to sum the outputs of all eight comparators to get a mixture of pulse-width-modulated waveforms, adding a slightly different effect. It is also useful to add a pot to control a mix of original sawtooth and phase shifted sum. The module requires very little panel space (two or three jacks, and possibly a pot).

APPLICATIONS OF THE MULTI-PHASE WAVEFORM ANIMATOR (MFWA)

The basic application of the MFWA is simple - it is just an add on unit for the sawtooth output of a VCO, and you will use it as shown in Fig. 7a, exactly as you would

Fig. 6 Full Circuit of Multi-Phase Waveform Animator
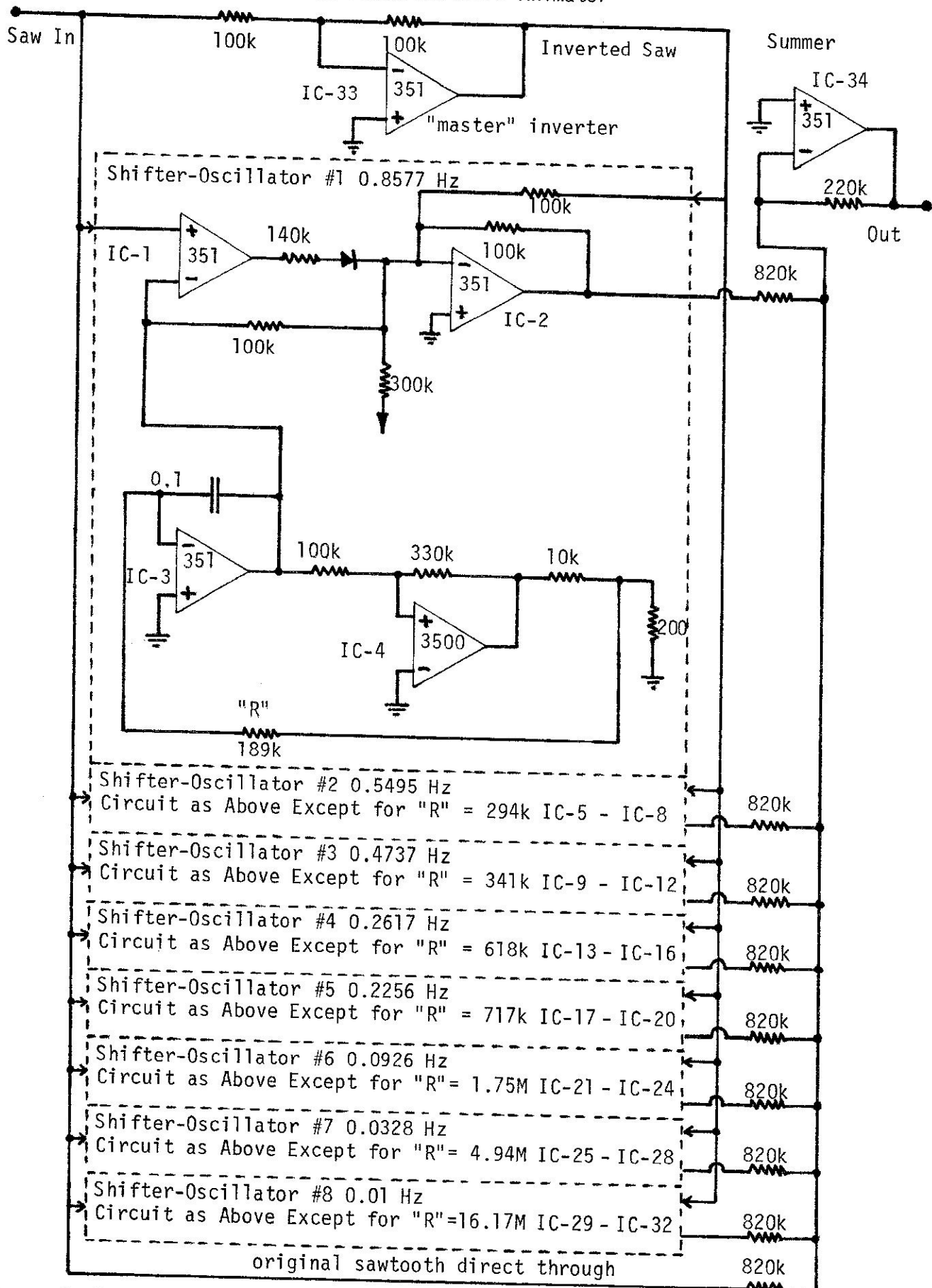
Notes: Op-Amp IC-4, etc., marked 3500 may be BB3500, 307, 741, etc.
All "R" resistors may be closest 5% value to value listed.
For different operating frequencies, choose "R" from Table 1

the VCO by itself.   The difference is that you will be starting out with a richer sound to begin with.

The MPWA will respond to any waveform that has continuous level changes (saw, triangle, sine) but not to those that have only sudden jumps (square, pulse). We can thus input a sine as in Fig. 7b, but we should not be confused into thinking that we are phase-shifting the sine. The MPWA in this case is chopping up the sine and mixing the pieces back together again. The result is an output not unlike that you get with a sawtooth input, but one which has a somewhat milder "edge" to it. The triangle input is somewhere between the saw and the sine.

Fig. 7a

Fig. 7b
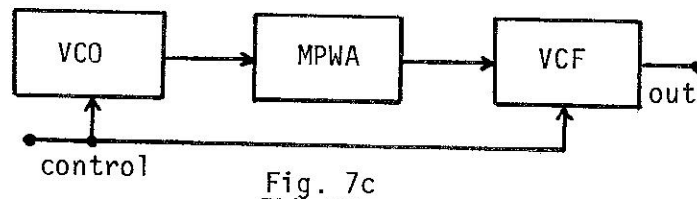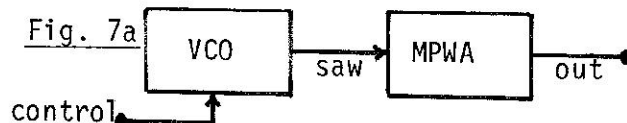
Fig. 7c

It is of course possible to add filtering to the MPWA output as shown in Fig. 7c, and thereby reduce the harshness of the sound to any desired degree.   This works quite nicely in fact.   Keep in mind that the VCF need not be placed specifically as shown in Fig. 7c. It may in fact just be the VCF you probably intend to use somewhere in the patch anyway. The voltage-controlled high-pass mode is also useful here.

It is felt that for the relatively low parts cost of the device ($15 to $20), its low demand on panel space, the relative ease of construction, and the simple operation, that this module is a very valuable addition to a traditional collection.

    *   *   *   *   *   *   *   *   *   *   *   *   *   *   *   *

Minimum Parts Count Synthesizer: -by Dave Rossum, Eμ Systems

Ron Dow of Solid State Music and I have now completed our family of integrated circuits for synthesizers. These circuits, which include a voltage-controlled filter building block, a wide range voltage-controlled oscillator, a voltage-controlled ADSR type transient generator, a dual Gilbert multiplier VCA, and an ultra low noise VCA, were designed to enable the engineer to make a complete synthesizer using a minimum number of components.

The chips may seem too expensive for their functions compared to discrete designs if one merely counts component prices. Such a comparison is deceptive; it has recently been pointed out to me that the actual cost per IC in TTL designs is $1.24, even though the parts themselves cost about 12 cents.   This figure takes into account board space, assembly time, and more notably debug time, reliability, and field service costs (if there are fewer parts, there is a lower probability of failure, and the failure is easier to find). Hence, in terms of production, replacing four packages with one can justify a $5 price tag.

Particularly in electronic music, where technology is advancing rapidly, these IC's present another advantage, that of design ease.   By using these large scale circuits, the engineer can simplify the design cycle and spend more of his time concentrating on the systems aspects of his product. An excellent example is the newly announced Prophet 10 from Sequential Circuits, the world's first fully programmable 10 voice polyphonic synthesizer. It was designed by Dave Smith, who is relatively inexperienced in analog