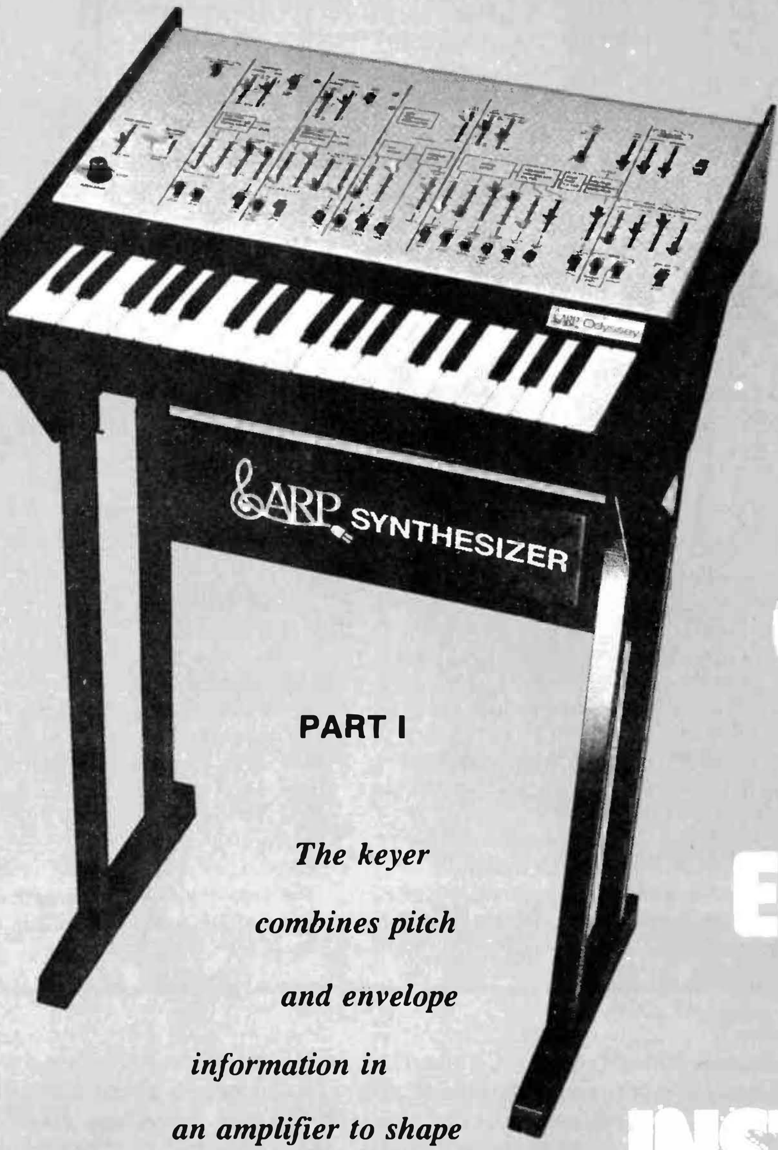
BY DON LANCASTER



KEYING & VCA CIRCUITS FOR ELECTRONIC MUSIC INSTRUMENTS

PART I

The keyer combines pitch and envelope information in an amplifier to shape a realistic mode.

KEYING circuits go by many names. In organs, they are called simply keyers; in traditional electronic synthesizers, they are often called voltage-controlled amplifiers (vca's), envelope shapers, or modulators. Functionally, they are electronic multipliers. All of them do the same job—they combine pitch information with the envelope information to produce a realistic note or note sequence.

Done properly, this sets the attack, sustain, fallback, decay, and snubbing of any note on an individual basis. Envelope control can also introduce such special effects as percussion, the "bite" on the leading edge of a horn sound, echos, tremelo, and noise modulation.

A very few older organs did not employ keyers. They simply applied and removed the supply voltage to and from oscillators or used the keys themselves as off/on note controllers. Envelope shaping ability is very limited by this means. At the other extreme, some true computer composing circuits and programs completely specify the amplitude and frequency instantaneously. With these exceptions, virtually every other electronic music system generates tones and envelope information separately. These two signals are then routed into a circuit that provides a combination of the desired loudness and frequency.

The keyer or vca might work on any note in a monophonic instrument, or one individual keyer can be supplied with each note in a polyphonic system. We can use much more sophisticated keying circuitry if we need only a few, rather than one for each note. Keying or envelope shaping can take place either before or after the tinbre or tone-quality circuitry, working either with the raw frequencies as generated or the final highly structured harmonic tone. Organs usually employ fixed formant filters; and a polyphonic instrument is usually keyed first and voiced later. In synthesizers, the note will more often be colored by a patchwork of voltage-controlled oscillators (vco's) and filters (vcf's), and then envelope shaping takes place.

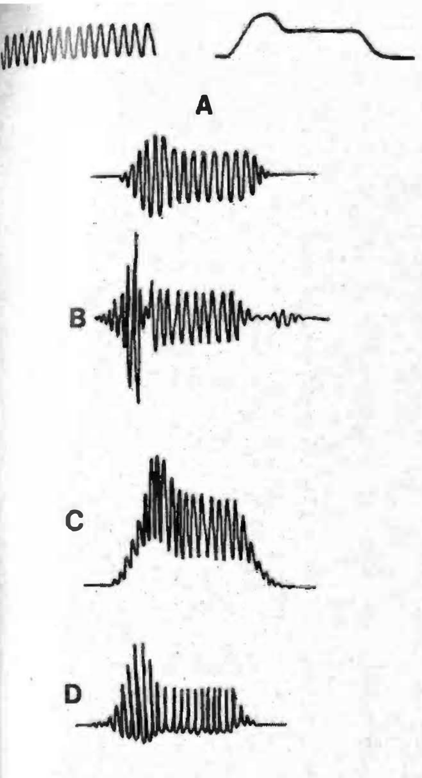


Fig. 1. In a good keyer, pitch and envelope waveforms (above A) are combined to produce a note which is their mathematical product (below A). Output of poor keyer (B) has excessive transients; (C) has envelope in output; (D) has unequal positive and negative swings.

What a Keyer Does. Any keying circuit must simply control the gain of the tones fed through it. In Fig. 1 are shown some good and some bad things keyers do. The keyer must behave as a linear, electrically bilateral variable resistor. Ideally, it must introduce no coloration or significant distortion of its own (Fig. 1A).

A keyer must be transient-free. This means that no ringing or overshoot can be permitted as in Fig. 1B. It also means that no feedthrough of the envelope information to the output can be permitted (Fig. 1C). The result of feedthrough is a loud thump and other response-recovery problems later on in the circuit. Any keyer circuit in which the dc output level changes as a function of the envelope command is bound to be a bad design and will thump badly.

A keyer must treat positive and negative signal swings equally, amplifying or attenuating them with equal gain (Fig. 1D). And the keyer system must have a wide enough frequency response to follow faithfully the envelope and pass all frequencies of the tone or waveshape without behaving like a low-pass filter.

To be useful in a circuit, the keyer should have a medium-to-high tone input impedance and a low output impedance so that it can drive output and timbre circuitry without difficulty and does not load down the tone source too heavily. The impedance at the envelope input would ideally be infinite so that large-value resistors and economical small capacitors could be used for attack-sustain-decay shaping. This is particularly important on polyphonic instruments where a hundred or more keyer circuits might be needed.

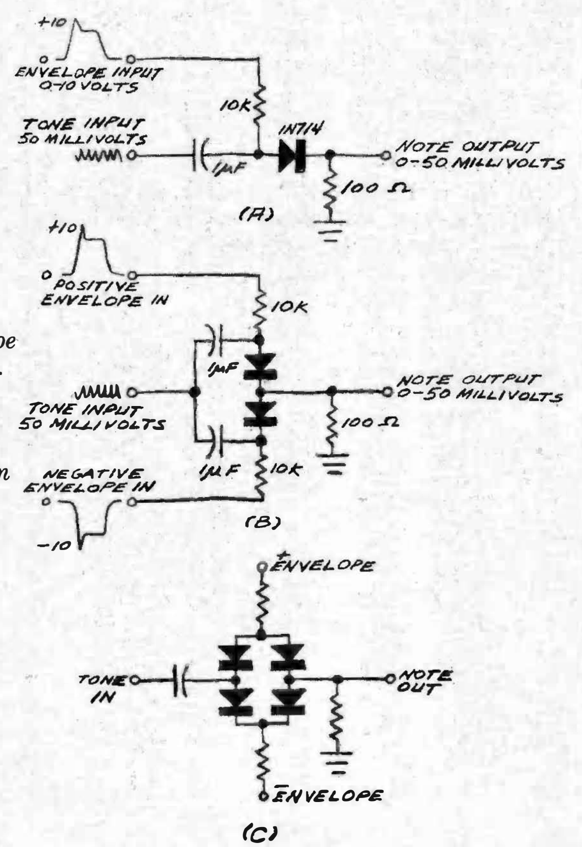
Keyer design is no simple task, since it shares all the woes of any faithful electronic analog or digital multiplication problem. Let us look at some popular approaches to keyer design. In this first part of our two-part article on keyers, we will discuss diode, differential-amplifier, four-quadrant multiplier, and gain block keyers. Next month, JFET, MOSFET, Transconductance-amplifier and CMOS keyers.

Diode Keyer. The diode keyer is by now, fairly obsolete. An ordinary silicon diode has its small-signal (50 mV or less) ac impedance set by the direct current through the diode. If there is no current, the diode is an open circuit. For small direct currents, the impedance presented to ac signals is given by the ratio 26/I, where I is the current in milliamperes. So, a diode carrying a 0.5-mA current "looks" like 52 ohms to a low-level ac signal routed through it.

In Fig. 2A, one capacitor is used to couple a tone into the diode and use the envelope information to set the direct current through the diode. The disadvantage of this circuit is that it will thump as the envelope appears in the output. A second diode and equal positive and negative signal swings (Fig. 2B) from the envelope circuitry overcome this disadvantage. The two diodes are in series across the envelope circuit but in parallel with the tone input. Two more diodes (Fig. 2C) eliminate the extra coupling capacitor.

Input impedance is low, output impedance is high, and a wide voltage swing into a medium resistive load is needed for the envelope input. But if the diodes are identical and if the control voltages are also identical, and if the ac signal level is low enough, the diode keyer can operate without introducing intolerable distortion, and it

Fig. 2. Simple diode keyer (A) thumps as envelope appears in output. Two diodes (B) eliminate most of output thumping. Four-diode version (C) saves one capacitor and has lower distortion.



will not cost much to make. (A diode keyer will always add some distortion.)

Various transistor schemes have been used in keying setups. They are basically diode keyers that use the base-emitter junctions of transistors as the multiplier elements. They ease the loading and impedance problems, but they can introduce thumping if they are not properly designed. Today, we have much better methods.

Differential Amplifier. In Fig. 3A is shown a differential amplifier. It is the most commonly used amplifying circuit at this time and is found in almost all linear integrated circuits. A differential amplifier normally amplifies the difference between two input signals. In Fig. 3A, one input is tied to ground to provide single-ended-input operation. This circuit can be used as a keyer by routing the tone signal into input X and the envelope into input Y.

If a fixed voltage is applied to input Y, some emitter current will appear in *Q1* and *Q3*. Input A goes to *Q1* and comes out of the transistor's emitter. The emitter signal drives *Q3*, which is operated as a grounded-base stage, and an amplified version of the input signal appears at *Q3*'s collector.

The gain of the circuit in Fig. 3A is obtained from the formula IR/104 where R is the *Q3* collector load resistance in kilohms and I is the emitter current in *Q3*, the 104 comes about because *Q3* receives only half the available current and because *Q1*'s output impedance is equal to the input impedance of *Q3*, which yields a second 2:1 attenuation.

It is important to note that the gain is directly proportional to the emitter current. Change the voltage on input Y, and the gain changes, and the product of the envelope and tone input signals is obtained. This type of circuit is called a vca. It bilaterally and at high speed gives the product of the two input signals.

One obvious problem with this circuit is that the dc drop across *Q3*'s collector load resistor follows the envelope, resulting in two output terms—the desired shaped tone and an undesirable thumping from envelope feedthrough. In Fig. 3B, a second load resistor, in the collector circuit of *Q1*, has been added. This circuit has two outputs, one of which is in-phase and the other out-of-phase with the input. Both outputs bounce up and down together.

A good differential amplifier ignores the common-mode up-and-down bouncing of the input signals. It is only the difference between the two signals that matters. So, by simply adding still another differential amplifier stage to the one shown in Fig. 3B, the output stays at a fixed dc level regardless of the envelope and is a thump-free replica of the desired signal.

Differential amplifiers are widely used in synthesizer vca's. While many similar devices exist, the RCA CA3000 series linear IC's offer many differential-amplifier possibilities. An ordinary 741 or 5558 operational amplifier can be used to eliminate the common-mode thumping on the last stage. The differential-amplifier vca offers good input and output impedances, controllable gain, and large signal swing. The envelope signal must be referenced to a negative supply, and the input impedance might be a bit lower than we would like it to be. Dynamic range is good and distortion is low, but the system becomes a bit complex if a separate circuit is used for each polyphonic note. The differential-amplifier vca is a very good choice for monophonic synthesizer circuits.

Four-Quadrant Multiplier. A four-quadrant multiplier is a true electronic multiplier that provides the product of the envelope and pitch inputs directly. No offsets are needed on the envelope input, and the output is normally referenced to ground.

A typical four-quadrant multiplier circuit is shown schematically in Fig. 4. The multiple paths through all the differentially-arranged transistors provide for automatic cancelling of common-mode feedthrough and thumping. As a sometimes handy gimmick in some advanced synthesizers the phase of the tone signal is reversed by inverting the envelope.

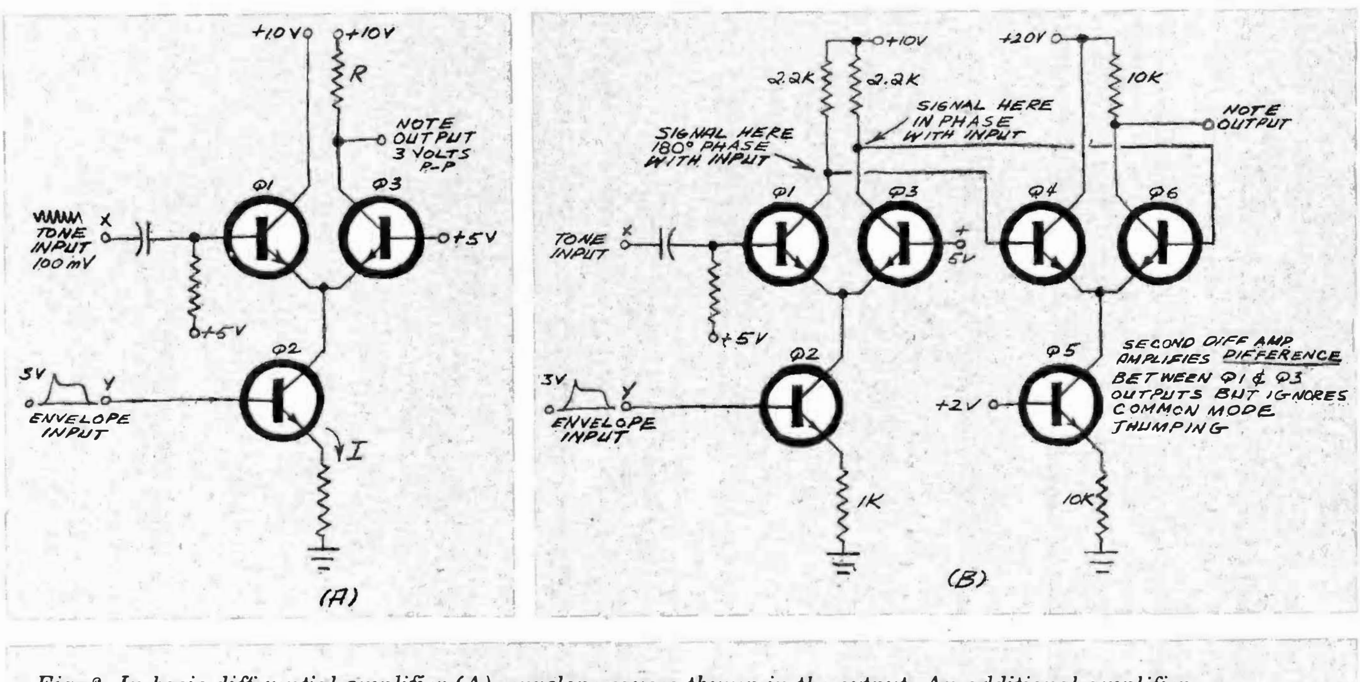


Fig. 3. In basic differential amplifier (A), envelope causes thump in the output. An additional amplifier can be added (B) to eliminate thump. Second stage can be an ordinary 741 operational amplifier.

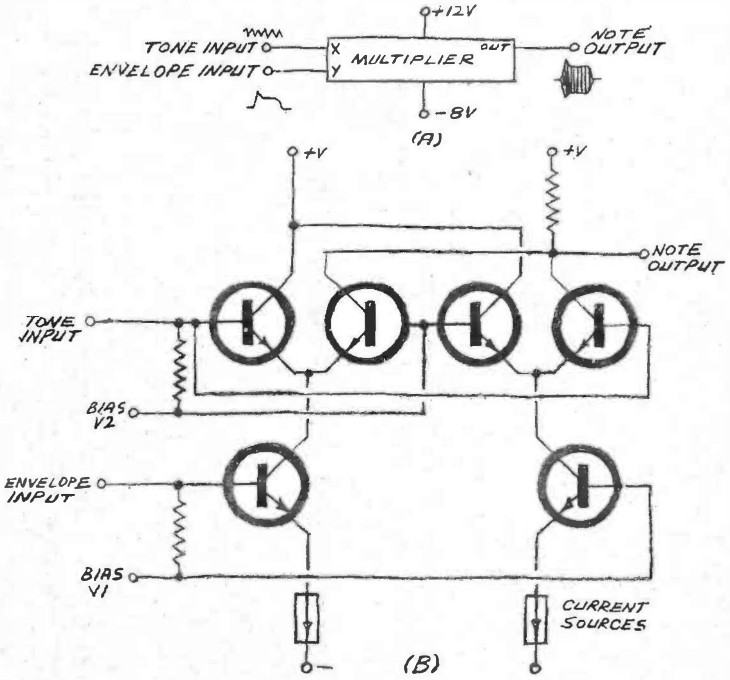


Fig. 4 (A) are typical connections for 4-quadrant multiplier. Key internal circuitry is shown at (B).

Typical four-quadrant multiplier IC's include Motorola's MC1595 and Analog Devices' AD532. Alternatively, you can use the much lower priced Signetics 5596 as the key component in a multiplier of your own design.

The only real disadvantage with the four-quadrant multiplier is its cost. None of these IC's is inexpensive. Some exceed $20 each and obviously are too costly if you are considering using one for each note in a polyphonic system. Aside from this, the four-quadrant multiplier is just about the best you could hope for.

Gain Block. Several linear IC's offer remote-controlled gain capability that can be used as a keyer circuit. Motorola's MFC6040 is a typical example of such a circuit (Fig. 5). It costs about $1. Its circuit is one more variant on the differential-amplifier theme

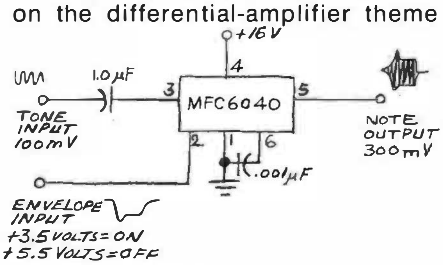
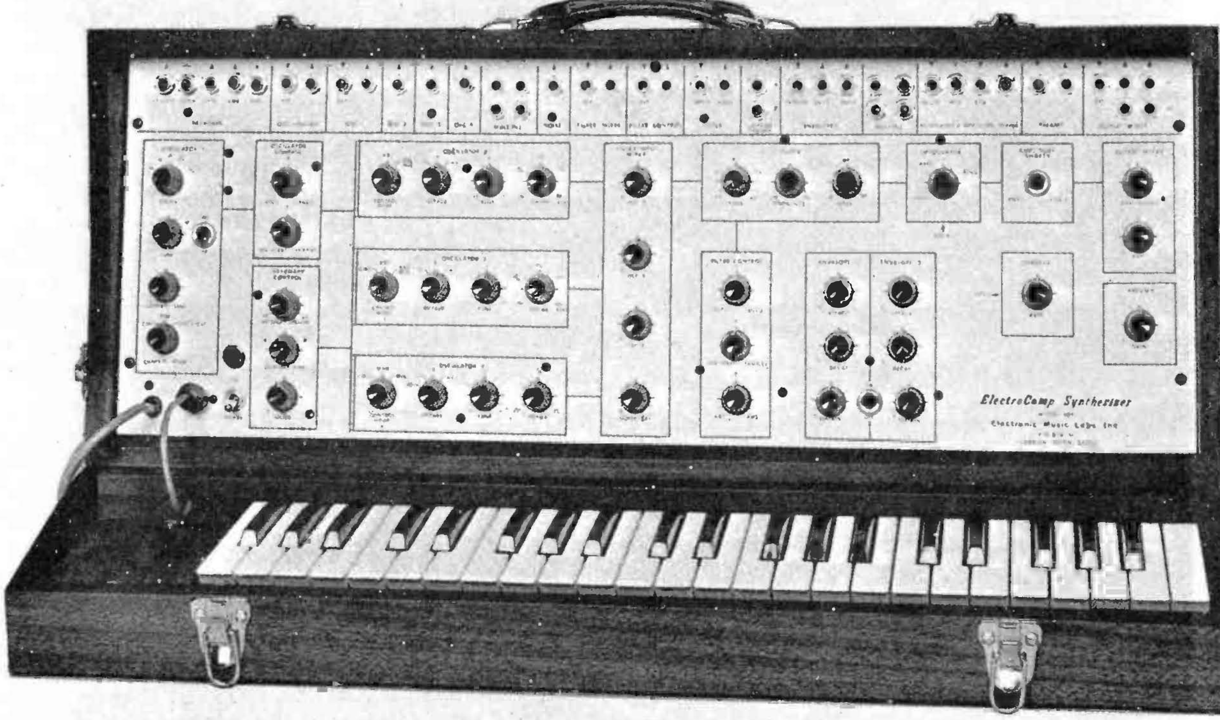


Fig. 5. Gain block envelope shaper.

with common-mode bucking. Typical voltage gain, wide open, is 3:1 or 10 dB; attenuation can go as low as 70 dB below full output.

The output swing of the MFC6040 can be up to 6 volts peak-to-peak. One potential disadvantage of the circuit is that the attenuation is somewhat nonlinear. ◈



KEYING & VCA CIRCUITS FOR ELECTRONIC MUSIC INSTRUMENTS

PART 2

Gain-block IC, JFET, MOSFET, CMOS and digital keyers

By DON LANCASTER

LAST MONTH, Part I discussed what a keyer does and several different types of keyers and vca's used in electronic musical instruments. We continue here with descriptions of other types of keyers, including the digital variety.

A Special Gain Block. The CA3080 is a special, inexpensive gain-block IC made by RCA. It can serve either as a voltage-controlled amplifier (vca) or as a two-quadrant multiplier, making it almost ideal for use in electronic musical instruments.

A typical circuit in which the CA3080 is used is shown in Fig. 1. While the IC looks like an ordinary operational amplifier (the connections are about the same as for the 741 op amp, in fact), there are some important differences. First, the output is a bilateral current coming from a very high impedance source. Second, the internal current gain is linearly variable from zero up by controlling the current fed into pin 5 of the IC. Zero current provides zero gain, while +100 μA provides a maximum useful gain.

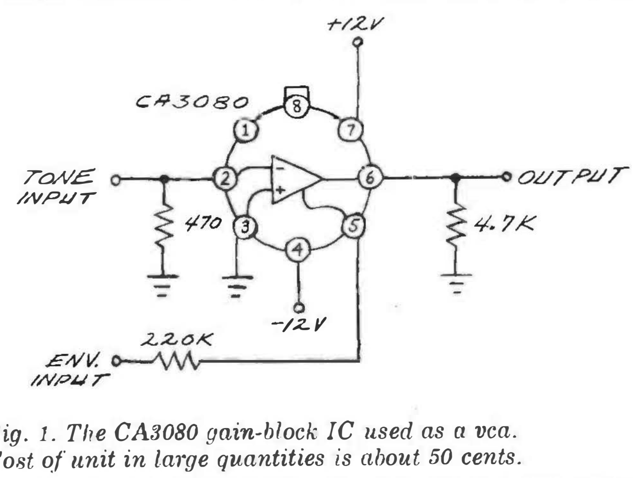


Fig. 1. The CA3080 gain-block IC used as a vca. Cost of unit in large quantities is about 50 cents.

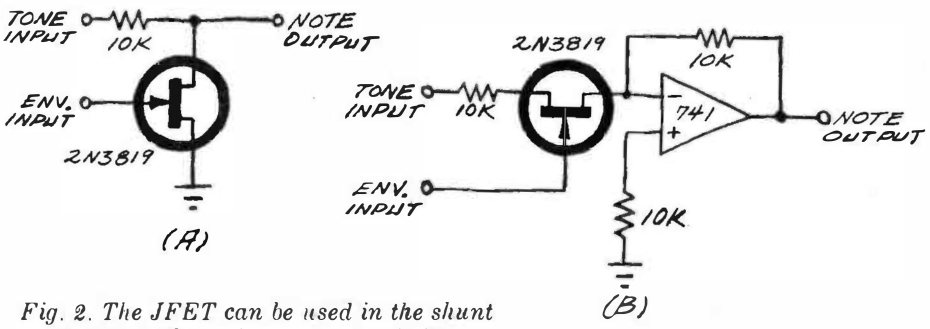


Fig. 2. The JFET can be used in the shunt mode (A) or the series mode circuit (B).

There are two inputs to the IC, inverting (−) and noninverting (+). The IC amplifies the difference voltage on these inputs and converts it to an output current. When an output load resistor is put into the circuit as shown, the output current is converted to an output voltage. Therefore, the overall voltage gain is set by the load resistor *and* the control current fed into pin 5.

There are three important things to remember when using the CA3080: (1) always keep input signal levels below 100 mV to prevent distortion and clipping; (2) always current-limit the input to pin 5 with not less than 100,000 ohms; (3) the voltage gain obtained depends on the output load resistor.

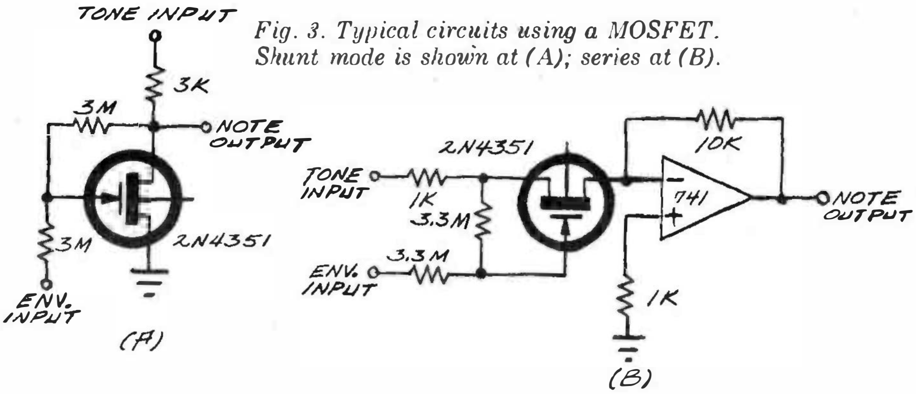


Fig. 3. Typical circuits using a MOSFET. Shunt mode is shown at (A); series at (B).

The JFET. The junction field effect transistor (JFET) can serve as a small-signal, electrically variable resistor. JFET's are low in cost. Texas Instruments' 2N3819 is a typical example of such devices. Also, there is a wide variety of custom JFET's for variable-resistance applications, with Siliconix offering several devices and some good application notes.

The ac input signal to a JFET must be kept very low in amplitude, preferably less than 10 mV peak-to-peak. Grounding the gate input of an n-channel JFET causes the device to conduct heavily. As the gate is made more and more negative, the equivalent resistance increases until the cutoff voltage is reached, at which point the JFET acts as an open circuit.

A JFET must be used in a shunt mode (Fig. 2A), or the signal into the virtual ground of an operational amplifier in the series mode (Fig. 2B) must be summed to keep the control or envelope voltage from appearing at the output.

The input impedance on the control line is very high because a reverse-biased diode is being driven as an input. One problem is that the cutoff voltage varies quite a bit from one JFET to another. Thus, it may be necessary to adjust the envelope amplitude and off level to suit the particular JFET in use.

The MOSFET. Enhancement-mode MOS (metal-oxide silicon) FET's with insulated gates can also be used as variable resistors. MOSFET's cost a bit more than conventional JFET's, but they have a number of distinct advantages.

Shown in Fig. 3 are typical circuits in which the 2N4351 MOSFET is used in the shunt (A) and series (B) modes. If the substrate lead is permitted to float and the two-resistor feedback network is used exactly as shown, the circuits can be operated with up to 10 volts of peak-to-peak audio signal.

A voltage must be applied to the gate of a MOSFET to drive the device (unlike the depletion-mode JFET that requires that a voltage be removed from the gate to turn it off). This permits the use of positive envelope and control voltages.

The MOSFET remains cut off until the envelope input signal reaches +4 volts or so. Between +4 and +8 volts, control of gain and resistance is more or less linear. Any potential beyond +8 volts or so does not significantly change the resistance.

The input impedance to the MOSFET is essentially infinite on the envelope line. However, the feedback resistors reduce the impedance to about 6 megohms, a value low enough to permit the use of small capacitors in the envelope shaping circuitry. At $2

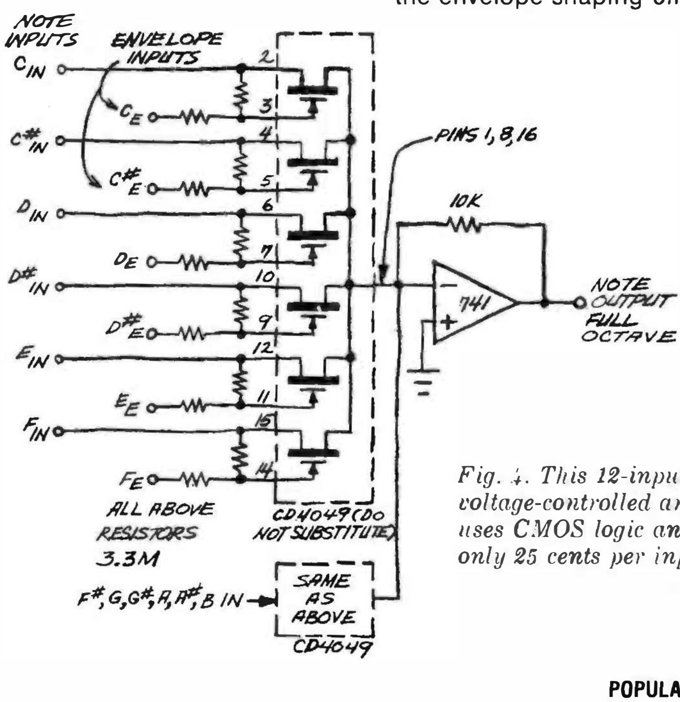
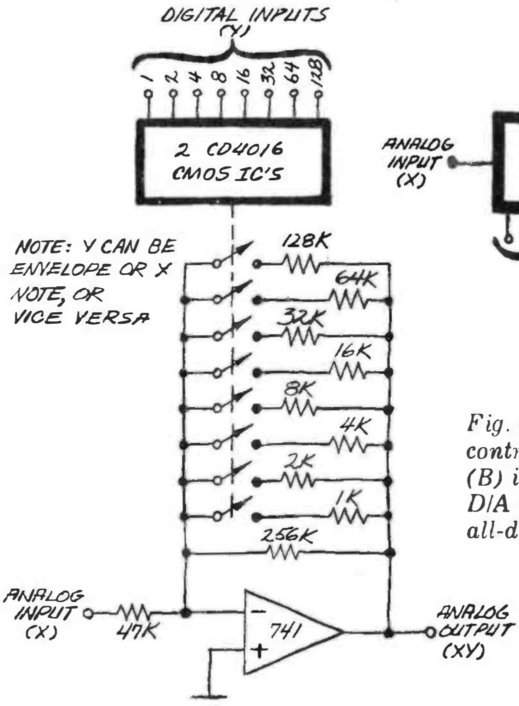
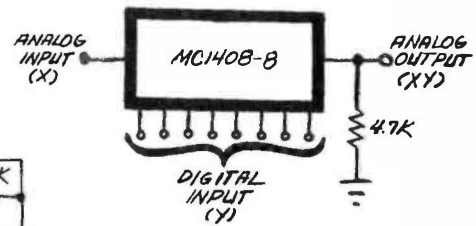


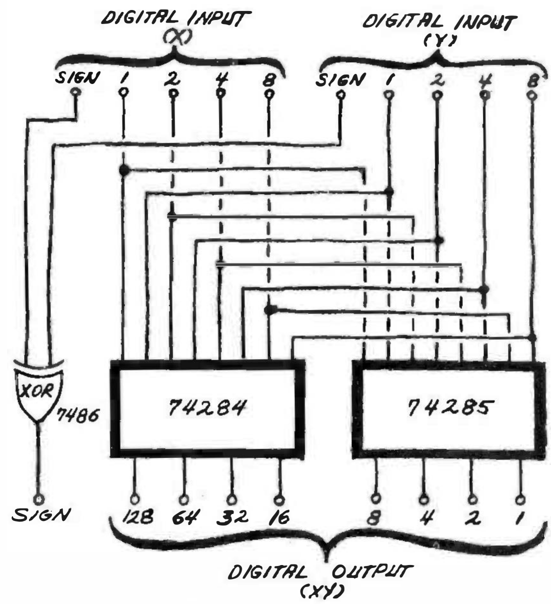
Fig. 4. This 12-input voltage-controlled amplifier uses CMOS logic and costs only 25 cents per input.



(A)



(B)



(C)

Fig. 5. At (A) is digitally controlled analog multiplier; (B) is economical but unipolar D/A converter; (C) is all-digital 5x5 multiplier.

or so per device, the MOSFET technique can be economically used on smaller polyphonic instruments.

The CMOS Technique. There are many games you can play with the CMOS digital-logic family of devices, especially the industry standard CD4000 series. One obvious thing to do is to bias a hex inverter to obtain six n-channel MOSFET's, yielding six keyers in a \$1 or \$2 package. The resultant unit keyer cost will then be 15c to 30c, which is the pricing you must aim for when considering a fully polyphonic keying system on a large but reasonably priced instrument.

The only catch to the above is that ordinary CMOS hex inverters contain input-protection diodes that make this essentially impossible. But the new RCA CD4049 or Motorola MC14049 IC's eliminate the problem. The circuit for using these new IC's is shown in Fig. 4. It is simply the circuit shown in Fig. 3 repeated 12 times for a full octave's worth of keying (12 notes), accomplished with three low-cost integrated circuits.

The signals must be limited to very low levels at the note inputs, preferably to between 50 and 100 mV rms from a 400-ohm source. Thanks to the operational amplifier, the output impedance from the system is low. The output signal level is 2 volts peak-to-peak. The resistors provide a linearizing effect. Depending on your system, however, you may be able to eliminate the resistors. It all depends on the distortion permissible at this point in your system. Since each keyer works on only one note, distortion changes the harmonic structure of only the one note and does not intermodulate.

The most important advantages of the CMOS keying approach include very simple circuit design, low parts cost and, electronically, very high impedance on the envelope input lines. (A fully custom version of the Fig. 4 circuit technique is used by one major electronic organ manufacturer.)

While you are looking at CMOS devices, check out the quadrature analog gate CD4016 IC. It cannot be used in a variable-gain mode, but it is great for on/off control of electronic music signals. Even in single-quantity prices, it costs only about 25¢ per channel.

Going Digital. So far, only analog keying and control techniques have been described. Digital techniques can also be used in electronic music. You will be seeing more EM digital circuitry in the future. Let us take a brief look at some of the possibilities:

In Fig. 5A, eight stages of CD4016 CMOS IC switching are used to set the gain of an operational amplifier to one part in 256. The gain can be set to any of 256 discrete values that are close enough that they appear to continuously change in amplitude.

The tone signal is fed to the input of the operational amplifier, and envelope information is derived from a mask or a digital memory. The memory can be in the form of a permanent store, program card, or programmable information store. One benefit of this approach is the ability to generate *any* envelope you want, including waveshapes that would be physically impossible with conventional acoustical instruments. Precision resistors are required for this particular circuit.

In Fig. 5B, all switching is accomplished inside the Motorola MC1408P-8 IC. An analog input current and a digital word are applied to the inputs. The output current is a ratio of the input current from zero to full value in one of 256 discrete steps. This circuit is also useful for changing a digital to an analog envelope waveform, or for converting digital timbre information into an equivalent analog waveshape. One limitation of the device is that the input current must be single-directional with respect to ground; so, an MC1408P-8 cannot be used directly for keying operations.

In Fig. 5C is a 5-bit by 5-bit (5X5) digital multiplier that provides a digital word as the product of an input envelope word and an input tone word. The five bits are derived from a pair of 4X4 multipliers and an exclusive-OR gate to take care of the sign bits. Though we would like to see more bits than this, the cost rises considerably if you shoot for greater accuracy.

There you have the keying and vca techniques commonly used in electronic musical instruments. Good luck in applying these to your own instrument designs. ◈