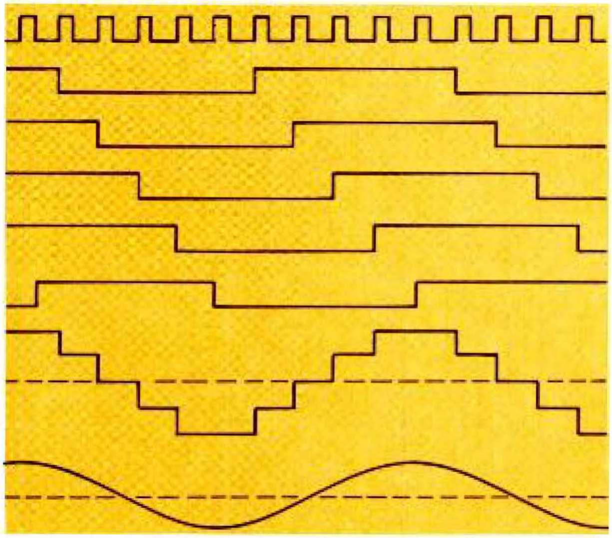


Create Sinewaves Using Digital IC's

Digital techniques can be used to synthesize sinewaves whose amplitude and frequency can be precisely and rapidly controlled and whose distortion is low

DON LANCASTER

EVERY ONCE IN A WHILE A REALLY GREAT IDEA gets buried deep in the technical literature. For instance, back in 1969, a very elegant and ultra-simple way to generate sinewaves digitally appeared. Then, apparently, it was nearly forgotten. Today we can use a $1.00 CMOS integrated circuit, three or four 5% resistors, and this "lost" method to build ultra-simple digital sinewave sources—sinewave sources whose amplitude and frequency we can precisely and rapidly control, and whose distortion is very low. We can use sinewaves like these in electronic music, lab function generators, sweepers, microprocessor and minicomputer analog I/O, digital cassette recorders and MODEMS. But, you're sure to find lots more places where you can use these simple, quick and sophisticated techniques.

The basic idea

Any method of generating sinewaves digitally is usually a two-step process. First, you generate a convenient waveform that consists of a fundamental and some harmonics. Then you get rid of the harmonics by filtering them out. The trick is to pick a convenient waveform that has as few harmonics as possible to start with. We also want the harmonics to be as small as possible, and we want them to be as high an order as possible. All these requirements simplify our filtering and let us change frequency over a reasonable range without necessarily changing our filtering.

Our search for a convenient waveform starts with a *symmetrical* one. This automatically gets rid of all the even harmonics. From here, we want to pick some waveform that inherently doesn't have as many of the odd harmonics as is possible. Ideally, we'd like to get rid of all the low-order odd harmonics. Directly using squarewaves doesn't look too promising because of a third harmonic only 10 decibels ($\frac{1}{3}$ amplitude) down from the fundamental that's staring you in the face. Similarly, most any relatively simple system based on binary counters will probably also have lots of strong, low-order odd harmonics.

The secret of digital sinewave generation is shown in Fig. 1. You use a circuit called a *walking-ring* or a *Johnson* counter to ultimately generate your sinewave. You make the counter as long as you have to. The longer the counter, the more parts, but the higher the odd harmonics you end up with and the weaker they are. A second part of the secret is that you combine outputs of the counter with resistors, into either a single small-value summing resistor, or into the summing input on an operational amplifier. *But you skip one counter stage in your summing.* This makes our sinewave waveform take twice as long automatically on the peaks and valleys. As we'll shortly see, the waveforms look rather strange and choppy before filtering, but *they have no low-order harmonics!*

You can make a walking-ring counter out of type-D flip-flops or out of many different types of shift registers. The CMOS 4018 is ideal for 6, 8, and 10-step sinewave synthesis, as we'll shortly see, and several 4018's can be cascaded for longer sequences. Our ten-step system takes only one 4018 (or five type-D flip-flops). Pick the resistors just right, and the first harmonic after the fundamental is the *ninth*, and it's almost 20 dB (one-tenth amplitude) down from the fundamental *before* you do any filtering. The only other low-order harmonics are the 11th, the 19th, 21st, 29th, 31st, and so on. All these are so low in amplitude and so high in frequency that if you get rid of the ninth by low-pass filtering, the rest will utterly disappear.

A type-D flip-flop or a register stage is a clocked logic block. When an input clock arrives, information on the D input is passed onto the Q output and its complement is passed onto the $\bar{Q}$ output. (If D is a "1", clocking puts a "1" on Q and a "0" on $\bar{Q}$. If D is a "0", clocking puts a "0" on Q and a "1" on $\bar{Q}$.)

To build a walking-ring counter, connect the Q output of one stage to the D input of the next stage and so on down the line. At the last stage use the complementary $\bar{Q}$ output to feed back to the D input of the first stage. If we use a five-stage register and start with

00000, one clocking gives us 10000 since the $\bar{Q}$ output of the last stage was a "1" and gets passed on to the first stage. More clockings give us 11000, 11100, 11110, and 11111. The $\bar{Q}$ output is now a 0, so the next clocking gives us 01111, 00111, 00011, 00001, and finally 00000, repeating the ten-step sequence as we close the series. The length of our sequence is ten or twice the number of stages.

The sequence length usually equals twice the number of stages in use. If we look at the five outputs A through E in Fig. 1, we see that we get a group of five *phase-shifted* squarewaves. We now sum *four of these five waveforms* with just the right "magic" resistor values, and we get a composite waveform that is a fundamental sinewave along with low-amplitude ninth, eleventh, and a few very small and very high-order remaining odd harmonics. For many uses you can use this sinewave pretty much as is, but it's a simple matter of filtering to get a sinewave of good purity.

Our clock frequency sets the output frequency. With a five-stage, ten-step system, the clock input is ten times the output frequency. As the clock frequency changes, so does the output on a nearly instantaneous basis, since there are no time constants or inductors in the circuit. Note also that a sudden change in clock frequency *coherently* changes the sinewave without any transients or jumps.

With CMOS and relatively light loading (20K or more) the output logic swing is equal to the supply voltage, so we can change the output amplitude either by changing the supply voltage or by changing the gain (digitally or otherwise) of any op-amp that's summing our phase-shifted squarewaves into the composite sinewave output.

Circuits

Figs. 2 and 3 show us two circuits using a single 4018 CMOS register that you can use for digital sinewave generators.

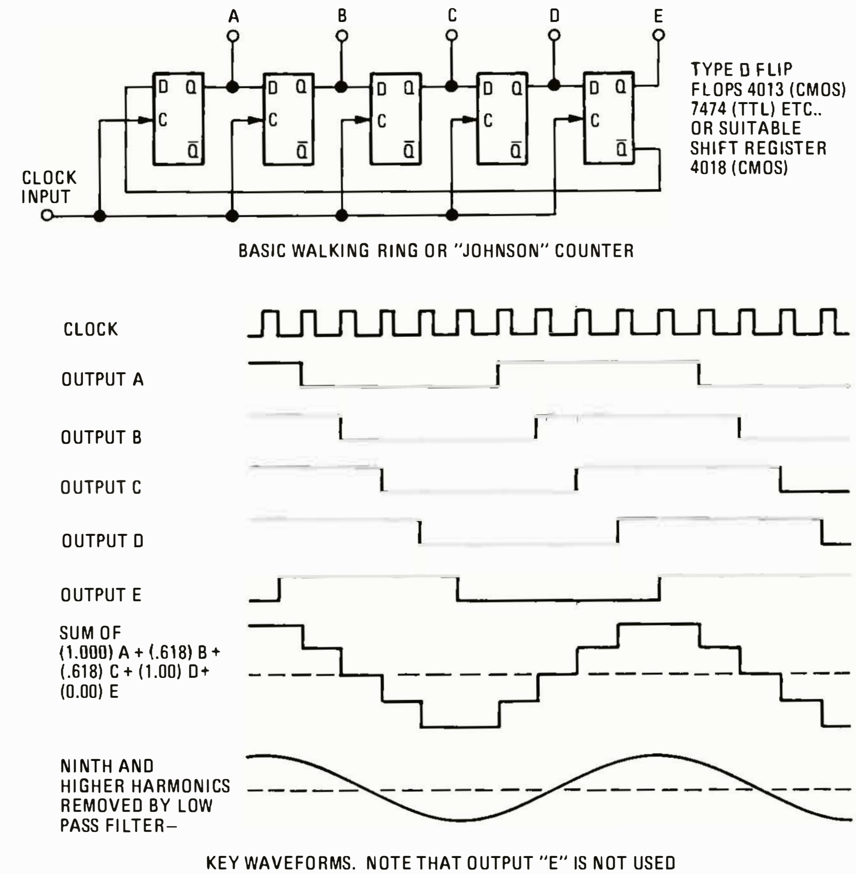
In Fig. 2, we've built a four-stage counter that gives us an eight-step output using one IC and three resistors. The output is summed across the 4.7K resistor and then actively filtered by the PNP emitter follower and the third-order Bessell active filter. This particular circuit is used in a digital cassette recording system, where a digital "1" is a 2400 hertz and a digital "0" is a 1200 hertz sinewave recorded on the tape. You can shift the cutoff frequency of the active filter by proportionately changing capacitors C1, C2, and C3. Doubling these capacitors reduces the cutoff frequency in half and so on. The input clock of this circuit is eight times the output frequency.

In Fig. 3, we have a five-stage counter and four resistors that sum into a type-741 operational amplifier. The op amp is filtered with a single capacitor. This particular circuit drives the transmitter speaker of a "103" style MODEM, outputting a 1070 hertz sinewave for a digital logic "0" and a 1270 hertz sinewave for a digital logic "1". This time the clock frequency is ten times these output values.

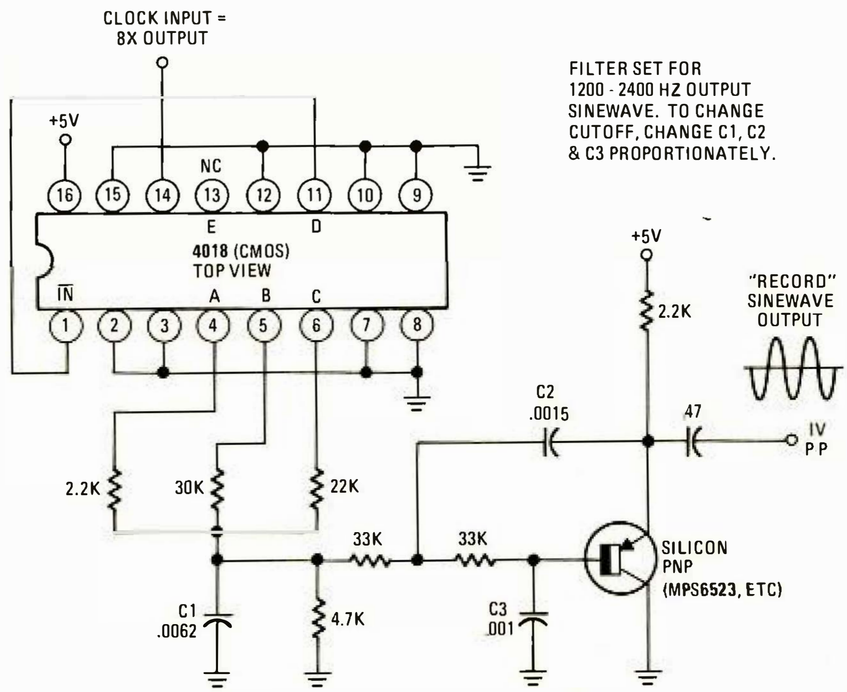
Magic numbers

Figures 4, 5 and 6 show us the magic resistor values, the circuits, and the waveforms for three, four and five-stage registers of length 6, 8, and 10. The value in parenthesis is the resistor ratio we want, while the

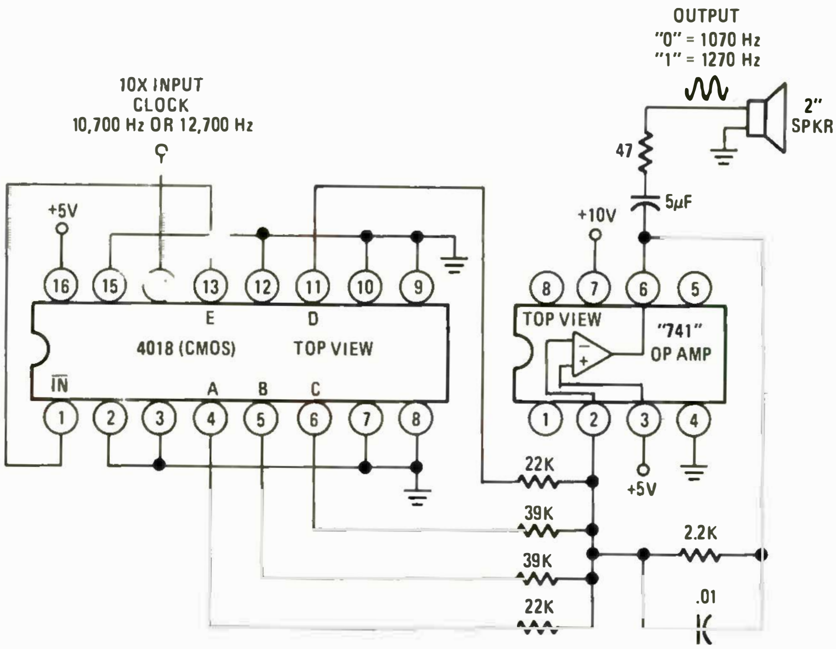
1. THE WALKING RING COUNTER and its waveforms, which combine to produce a good sinewave (after filtering).



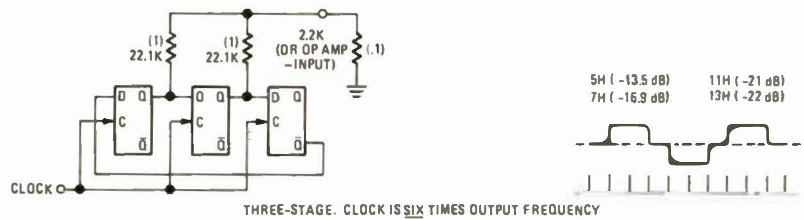
2. AN EIGHT-STEP GENERATOR, as used in a digital cassette recording system.



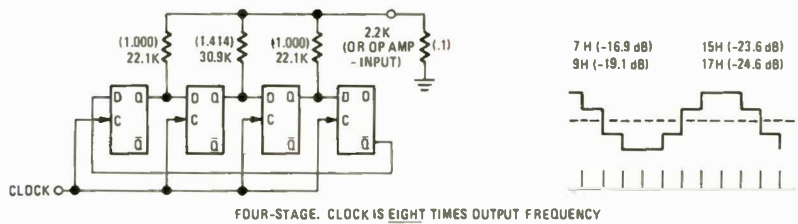
3. **10-STEP SINEWAVE GENERATOR drives the transmitter speaker of a MODEM.**



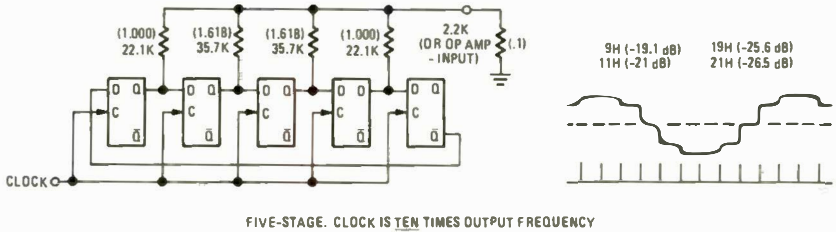
4. **THREE-STAGE DIGITAL SINEWAVE GENERATOR. Resistance values are shown in ratios (parentheses) and ohms. The amplitude of the harmonics are also shown.**



5. **FOUR-STAGE DIGITAL SINEWAVE GENERATOR.**



6. **FIVE-STAGE DIGITAL SINEWAVE GENERATOR.**



resistor value has been rounded off to a stock 1 percent value. Actually, 5 percent resistors are more than adequate for practically all sinewave generators, particularly for those of ten stages or less.

You'll get more performance by lengthening the registers and using more resistors. Values for any length are shown in Table 1, along with the harmonics and their strengths that you can expect. Once again, the parenthesis values are exact ratios, while the resistor values are 1 percent based on 22.1 K being the smallest value used.

These longer lengths make filtering more easy since the odd harmonics you do get are higher in frequency and lower in amplitude as you add stages. Note that the input clock frequency goes up as you add stages. Two or more 4018's can be cascaded as needed for these longer lengths. Usually binary lengths of 8 and 16 or decimal lengths of 10 or 20 make for the easiest interface with the system timing in the rest of your circuit.

Note that with a longer register, you can have a fixed filter and still operate over a wide frequency range. For instance, with a 10-stage register and a 10:1 frequency change, the lowest harmonic of the lowest output frequency will still be 1.9 times the frequency of the highest output frequency and reasonably easy to get rid of with a sharp-cutoff filter.

Some loose ends

You may have to look into several details when generating your own digital sinewaves. These include the counter sequences, resistor tolerances, offsets, and the choice of filtering.

Walking-ring counters longer than two stages have *disallowed sequences* that make up the difference between the total possible counter states and the states you are actually using. For instance, a three-stage counter has the valid 000, 100, 110, 111, 011, 001 and back to 000 six-count state sequence. It also has a disallowed 101, 010, 101, 010 . . . . two-count rut it can get into. All walking-ring counters must be set up to eliminate the disallowed states.

This is done internally in the 4018 counters, and cascaded 4018's will probably eliminate most if not all the possible disallowed sequences. You can also use a reset button or signal to get your sequence off on the 000 state before you begin. Or you can add gating to force the internal stages to zero when the end stages are zero; or to all ones when the end stages are ones. (If you have only a common reset line for all stages, be sure to shorten the reset pulse so it doesn't permanently hang up the register.)

How accurate do the resistors have to be? For registers of ten stages or less, a tolerance of 5 percent is good enough, even though we've shown you 1 percent values. Resistors out of tolerance introduce lower-order odd harmonics, but for most 5 percent variations, these should be 40 decibels below the fundamental or lower.

Note that there will be a DC offset in the output sinewave that usually must be eliminated somehow. The simplest way is with a blocking capacitor as we did with the output capacitor in Figs. 2 and 3. With our CMOS outputs, we have a choice of summing to the positive supply voltage, to ground, or to an op amp's inverting input biased halfway between positive supply and ground. In Fig.

TABLE I—DESIGN INFORMATION FOR LONGER GENERATORS

STAGES	CLOCK	RESISTORS*	HARMONICS
6	12x	22.1K; 38.3K; 44.2K; 38.3K; 22.1K (1.000) (1.732) (2.000) (1.732) (1.000)	11H (−21 dB) 23H (−27 dB) 13H (−23 dB) 25H (−28 dB)
7	14x	22.1K; 40.2K; 49.9K; 49.9K; 40.2K; 22.1K (1.000) (1.803) (2.248) (2.248) (1.803) (1.000)	13H (−23 dB) 27H (−29 dB) 15H (−24 dB) 29H (−29 dB)
8	16x	22.1K; 41.2K; 53.6K; 57.6K; 53.6K; 41.2K; 22.1K (1.000) (1.849) (2.412) (2.613) (2.413) (1.849) (1.000)	15H (−24 dB) 29H (−29 dB) 17H (−25 dB) 31H (−30 dB)
9	18x	22.1K; 41.2K; 56.2K; 63.4K; 63.4K; 56.2K; 41.2K; 22.1K (1.000) (1.877) (2.532) (2.879) (2.879) (2.532) (1.877) (1.000)	17H (−25 dB) 35H (−31 dB) 19H (−26 dB) 37H (−31 dB)
10	20x	22.1K; 42.2K, 57.6K; 68.1K; 71.5K; 68.1K; 57.6K; 42.2K; 22.1K (1.000) (1.896) (2.618) (3.077) (3.236) (3.077) (2.618) (1.896) (1.000)	19H (−26 dB) 39H (−32 dB) 21H (−27 dB) 41H (−33 dB)
16	32x	22.1K; 43.2K; 63.4K; 80.6K; 93.1K; 105K; 110K; 113K; (1.000) (1.961) (2.847) (3.624) (4.262) (4.736) (5.027) (5.125) 110K; 105K; 93.1K; 80.6K; 63.4K; 43.2K; 22.1K (5.027) (4.736) (4.262) (3.624) (2.847) (1.96) (1.000)	31H (−30 dB) 63H (−36 dB) 33H (−31 dB) 65H (−36 dB)
n	2nx	$1; \frac{\sin\frac{2\pi}{n}}{\sin\frac{\pi}{n}}; \frac{\sin\frac{3\pi}{n}}{\sin\frac{\pi}{n}}; \frac{\sin\frac{4\pi}{n}}{\sin\frac{\pi}{n}}; \ldots \frac{\sin\frac{(n-1)\pi}{n}}{\sin\frac{\pi}{n}}$	(2n − 1)H (1/2n − 1) (4n − 1)H (1/4n − 1) (2n + 1)H (1/2n + 1) (4n + 1)H (1/4n + 1)

*** The resistor values in parentheses are exact ratios; values in ohms are rounded off to stock 1 percent values.**

2, we've summed to ground so the emitter follower will have a reasonably constant emitter current and thus not distort the waveform. In Fig. 3 we sum to one-half the supply voltage to minimize the offset at the output even before capacitor coupling.

A final detail is filtering. Complete information on active filters appears in the *Active Filter Cookbook*. For some uses, the harmonics are high enough in frequency that they can simply be ignored. For others, a simple capacitor or two to introduce rolloff is all you need. For more critical uses, a better quality active filter is called for.

Sharp-cutoff low-pass filters using Butterworth or Chebyshev response curves have the advantages of producing very clean sinewaves with a minimum of circuitry. But these sharp filters have one possible drawback—if the input sinewave is changing or jumping between several frequencies, the filters will introduce *group-delay distortion*, or simple smearing that will generally mess up any sudden input frequency changes. Where you are suddenly or often changing input frequencies, use the higher-order "more gentle" Bessell active filters since Bessell filters are designed to absolutely minimize this form of distortion.

These circuits actually make digital sinewaves easier and simpler and cheaper than analog ones, so there should be all sorts of things you can do with them. Let us know what uses you come up with. **R-E**

FOR MORE READING:

Generating digital sinewaves—
"Digital Generation of Low Frequency Sinewaves," Anthony C. Davies, *IEEE Transactions on Instrumentation and Measurement*, IM18, No. 2, June 1969 PP 97-105.

Active filters—
The Active Filter Cookbook No. 21168, Howard W Sams, Indianapolis, IN, 46206.

ELECTRONIC LANDMARK GONE

THE "GOLF BALL" 160-FOOT RADOME of the radar system built by RCA in southern New Jersey in 1959, is now a thing of the past. The Air Force reports that it has become unnecessary; its functions are now being performed at other radar sites.

Designed as a prototype for the Air Force's Early Warning system in the North, the 84-foot dome was constructed to withstand the 150-mph winds of the Arctic. It was made with nearly 1,650 interlocking hexagonal pieces, and one pentagonal piece at the top.

The "Golf Ball" was considered the most powerful radar in the world when it was designed. It could track a three-foot object 3,000 miles away. It has been used to track spacecraft, study eclipses, and take precise measurements of objects in space. Among its feats was a more precise determination of the value of the Astronomical Unit, the mean distance between the earth and the sun. This measurement has been valuable to scientists in determining orbital data on satellites and other planets more accurately.

FCC gets petition to permit stereophonic AM broadcasting

Kahn Communications, Inc., of Freeport, NY, has filed a petition asking that the Federal Communications Commission institute rule-making proceedings looking toward regulations that would allow AM broadcasters to operate sterephonically. The petition states that the Kahn AM stereo broadcasting system is completely compatible with standard AM broadcasting and does not degrade present broadcast service; and that it will allow AM broadcast listeners to enjoy stereophonic reception with little or no additional investment in receiving equipment.

The system has been demonstrated several times in on-the-air experiments, notably over WFBR, Baltimore, and was in use by station XETRA, Tiajuana, Mexico, for more than three years.

The Kahn system is a type of compatible single-sideband that can be received with two ordinary broadcast receivers, one tuned slightly below and the other slightly above the carrier frequency. A receiver designed to receive this type of AM stereo might have two IF's, one tuned slightly higher in frequency than the other.

An ordinary receiver tuned to the carrier receives both channels with the same results as if the station were using conventional modulation. **R-E**