Choosing a waveform generator: The devil is in the details

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All generators that use digital technology to create baseband analog waveforms are not alike—not even fundamentally. Yes, all such instruments use clocks, memories, and D/A converters. However, basic specs, such as word length, memory depth, and sampling rate, don't even hint at the rest of the things you may need to know about the units. Subtle variations in architecture can make a unit that is ideal for one application a disaster in another. Unless you've suffered the pain of a poor choice, you probably have no clue about how to pick the right generator for a task.

A useful place to start is with the names that describe the instruments. An "arbitrary waveform" is one that a user can define. Both "ARB" and "AWG" are short for "arbitrary-waveform generator." The acronyms describe units that elaborate on **Figure 1**'s basic architecture. "Arbitrary-function generator" (AFG) also usually applies to this type of instrument. "Synthesized-function generator" (SFG) and "function synthesizer" describe instruments that differ subtly from the others. The terms refer to instruments that replace the ARB/AWG clock generator with a circuit like that in **Figure 2**'s block diagram. This circuit is based on direct digital synthesis (DDS).

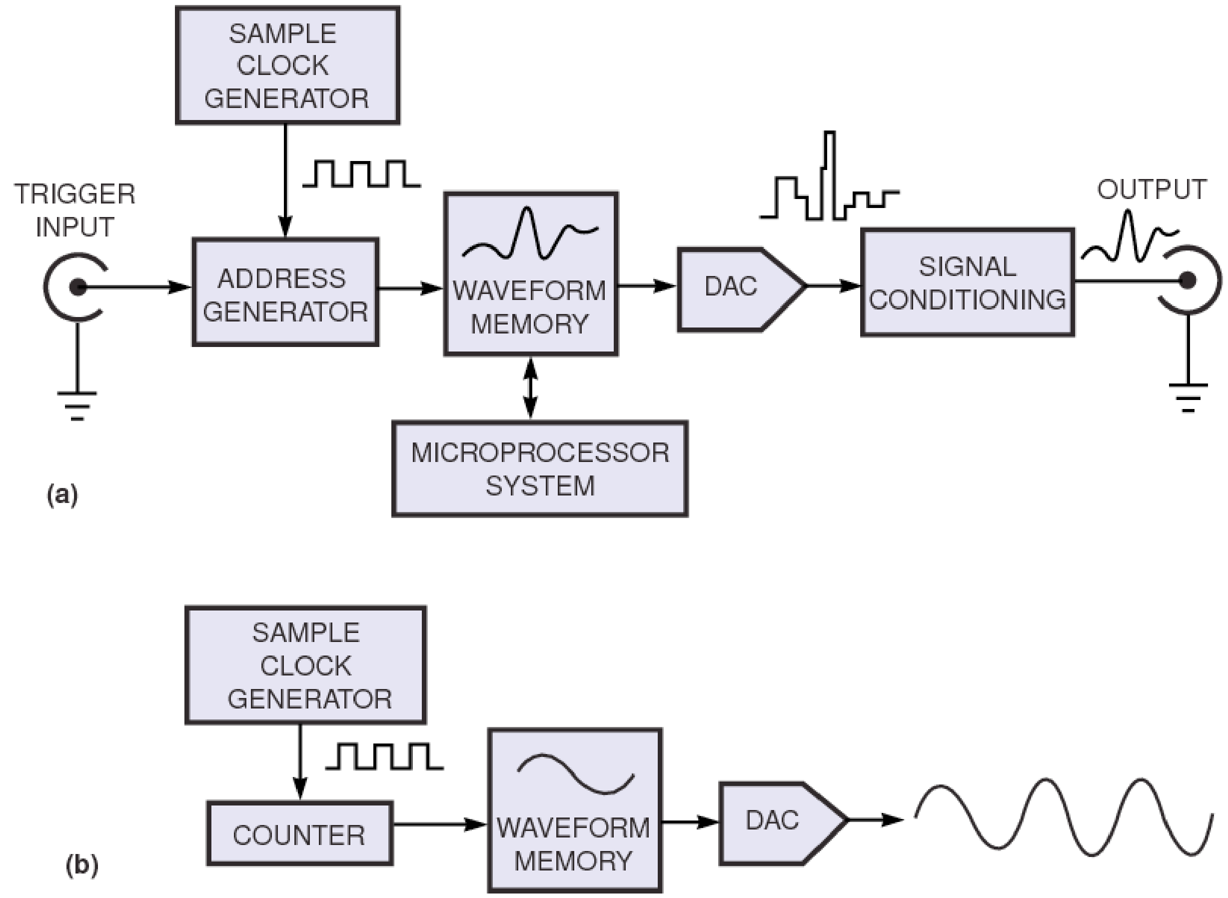

Figure 1

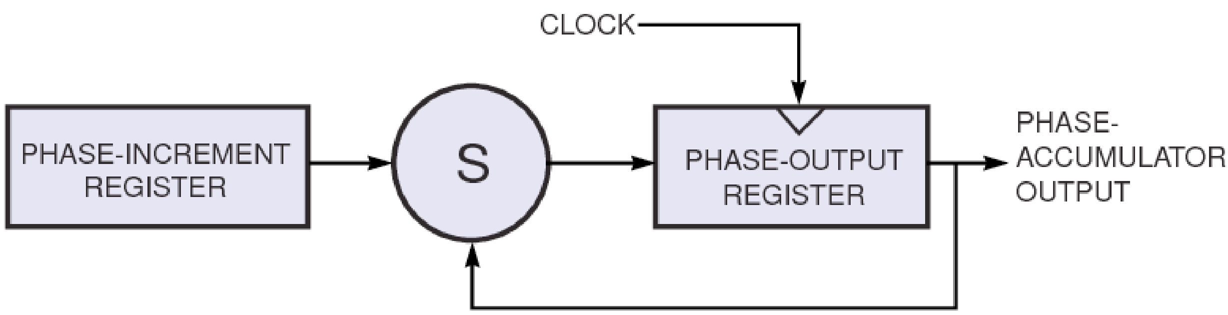

Figure 2

The terminology can be confusing because, besides arbitrary waveforms, ARBs can generate predefined functions, such as sine, square, triangular, and sawtooth waveforms. But generating these and other predefined signals is the mainstay of SFGs. To further complicate matters, many SFGs can also produce user-defined waveforms. Yet, despite these ARB-like capabilities, such generators aren't true ARBs. Because you can get both classes of waveform from both types of generator, you may wonder why you should bother to understand the differences between the generators. The reason is that each type of instrument excels at certain tasks and, depending on the application, may or may not perform other tasks satisfactorily.

Although this Design Feature uses the terms ARB, AWG, AFG, SFG, and function synthesizer consistently, manufacturers don't always concur in their use of the terms. It's wise to ask the supplier for a block diagram of any generator you are thinking of buying. If careful study of the diagram and the specifications don't convince you that the generator is right for your job, talk to an applications engineer. Ask pointed questions about how the unit performs in situations that are important in your work.

SFGs for predefined waveforms

An SFG is usually an excellent choice for applications that require only predefined waveshapes. However, many purchasers feel that the wisest investment is a generator that can also produce user-defined arbitrary waveforms. These buyers view the ability to produce user-defined waveforms as a worthwhile security blanket, especially if this capability adds little to the generator's cost. Nevertheless, users who actually need arbitrary waveforms may discover that SFGs' arbitrary-waveform capabilities aren't as useful as they had expected. For example, SFGs can have trouble producing waveforms such as low-duty-cycle pulse trains that exhibit fine detail.

The root of the problem is architectural and stems from the DDS technology that makes SFGs such a good value and such fine generators of standard signals. Despite their ability to produce outputs over wide frequency ranges, SFGs operate at a constant clock rate. The constant rate lets the generator manufacturer use low-cost, high-performance filters to remove digital artifacts from the output signals. Yet, thanks to a technique called "phase accumulation," you can set the output signal's repetition rate with extreme precision and vary it in tiny increments over many decades.

The ensemble of points that defines a waveform is called a "data set." Several modern SFGs have 14-bit-deep (that is, 16,384-point) waveform memories. Nevertheless, to produce one iteration of the output waveform, the generator generally doesn't send each of the data set's 214 points to the D/A converter. If the clock frequency is 50 MHz, only when the output repetition rate is exactly 50·106/214 Hz (that is, ;3.052 kHz) does each data point go to the DAC exactly once per output cycle.

At high output repetition rates, the phase accumulator skips points. At low rates, the circuit sends the same point to the DAC several times before moving to the next point. It is impractical to try to predict which points will go to the DAC and which will be skipped during any iteration of the waveform.

In the above example, at an output frequency just above the "magic" 3.052 kHz, most output cycles contain 214 points, but occasional cycles contain only 214-1 points. These cycles skip one point in the data set. Just below 3.052 kHz, most output cycles contain 214 points, but occasional cycles contain 214+1 points. In these cycles, one point in the data set goes to the D/A twice in succession. Not all cycles skip or duplicate points, however, and the duplicated or skipped points aren't always the same ones.

ARB-like capabilities

Adding ARB-like capabilities to an SFG is a relatively simple job for a generator manufacturer. The modifications involve the output filters and the waveform memory.

The output filter for arbitrary waveforms is a linear-phase (Bessel) design. This filter is the same one that the SFG uses to produce all of the predefined nonsinusoidal signals except square waves, which require no filtering. The Bessel filter delays all of the frequency components within its passband by roughly equal amounts of time.

To produce sine waves, the generators use an elliptic filter. This filter's sharp cutoff enables the generation of low-distortion sine waves to about 40% of the clock frequency. Unfortunately, this filter exhibits unacceptable overshoot and ringing in response to corners, spikes, and sharp edges in nonsinusoidal waveforms. The Bessel filter's more gradual stopband-attenuation-versus-frequency characteristic limits the maximum repetition rate of predefined nonsinusoidal functions to a few percent of the clock rate in some generators. The limitation can be even more severe for arbitrary waveforms, whose harmonic content can exceed that of the predefined waveforms.

To produce arbitrary waveforms, the generator must get waveform definitions from RAM instead of ROM. Besides changing the source of the waveform definition, some SFGs also let you adjust the arbitrary-waveform-mode memory depth. In several popular generators, you can choose memory depths that range from the full 16,384 samples to as few as eight samples. Sometimes, especially at high repetition rates, using a shorter data set can overcome problems with cycle-to-cycle repeatability of arbitrary waveforms.

The devil is in the details

You may now begin to see why it might be difficult for phase accumulation to produce waveforms with fine details—narrow pulses, for example. The most extreme case is a waveform whose amplitude is zero at 16,383 points and full-scale at one point. (For the moment, forget that the best source of such a waveform is usually a pulse generator, not a waveform generator.)

At high output rates, the phase accumulator skips past the one full-scale point on most passes through the data. At low rates, the accumulator dwells on the full-scale point (and all others) for multiple clock cycles before moving to the next point. In the high-rate case, the result is a waveform in which the pulse appears at unpredictable times. The pulse position thus exhibits substantial jitter. However, if the generator has a 50-MHz clock rate, the pulse width holds constant at one clock period (20 nsec). At low output rates, the nature of the problem changes: The pulse width is both excessive and unstable.

To reduce the likelihood of such problems, the generator may limit your choice of output repetition rates. For example, the generator may restrict your selection of arbitrary-waveform-mode repetition rates to ones that are integer submultiples of the clock rate. If the generator allows it, you can also choose a memory depth that sends each point to the DAC exactly once (or an integer number of times) in each waveform iteration. Remember, though, that because the generator has a fixed clock rate, these limitations can make it impossible to set the waveform repetition rate to a value you can use.

Considerations similar to those that affect the narrow-pulse waveform also affect waveforms that must be phase-coherent at frequency transitions. “Phase coherency” refers to the absence of discontinuities in waveforms whose frequency changes. When a sine wave makes a phase-coherent frequency change, the waveform’s slope can change abruptly, but sudden jumps in the instantaneous voltage are not allowed.

In a DDS-based generator, you change the phase accumulator’s phase increment to change the output signal’s repetition rate. The phase increment determines how many data points the generator skips between the ones it sends to the D/A converter. If you make an abrupt change in the phase increment—as you would to create a large frequency jump—the generator’s output voltage is likely to contain a phase discontinuity.

The preceding statement might lead you to believe that SFGs are not good generators of swept-frequency signals. In fact, the opposite is true. The ability to generate smooth linear and logarithmic sweeps over broad ranges is one of a DDS-based generator’s strong points. Frequency sweeps involve gradual frequency changes. An SFG generates a swept-frequency output by using a look-up table to gradually change the phase accumulator’s phase increment. The function in the table determines the nature of the sweep (linear or logarithmic, for example). In the sweep mode, phase discontinuities are normally small enough to be unimportant, especially when the output is a sine wave.

On the other hand, the inherent unpredictability of the fine structure of SFG outputs makes it impossible to exactly synchronize multiple SFGs. You can synchronize the generators’ master clocks, and you can make the units produce outputs at precisely the same repetition rate. But, except in special circumstances, you can’t guarantee that the generators produce identical waveforms on any output iteration. (A possible exception is at frequencies at which the generator uses each data-set point an exact integer number of times per iteration.)

This deficiency makes SFGs poor choices for driving the I (in-phase) and Q (quadrature) inputs of digital-communication systems' I-Q modulators.

True ARBs

For driving I-Q modulators and many other tasks, true ARBs are a better choice. ARBs' basic architecture is more obvious and possibly less ingenious than that of SFGs. ARBs use variable-frequency clocks, and, unless you tell them to do so, they do not skip or repeat data-set points in any waveform iteration. Moreover, ARBs send the data-set points to the DAC in sequential order.

Compared with SFGs, ARBs pay a penalty in output-filter cost and performance. If an ARB's maximum clock rate and an SFG's clock rate are equal, the ARB usually won't produce a sine wave at as high a frequency as the SFG does. In many cases, an ARB's sine-wave spectral purity is poorer than an SFG's. And many ARBs can't produce swept-frequency outputs over as wide a range as SFGs can. Moreover, the use of DSP-based techniques to reduce these penalties is likely to remain limited to lower frequency generators.

You might think that an ARB would also have trouble with the example's narrow-pulse waveform. After all, if the waveform memory stores a 16,384-point data set and the desired repetition rate is, say, one waveform every 16.384 msec, a 1-MHz clock rate seems to be required. The pulse width then becomes 1 μsec. Indeed, with a basic ARB whose memory depth is 16,384 points, you must run the clock at 1 MHz to produce a waveform of the required duration. Thus, if you need a 20-nsec-wide pulse, the generator produces a pulse 50 times as wide as the one you want.

Looping and branching

Many modern ARBs provide a neat way around this problem. By letting you break the memory into multiple short segments, these generators allow you to program the generator to cycle through one segment many times before moving to the next segment. Some of these generators can even perform conditional branches based on external stimuli. Depending on the state of an input, such a generator can jump to one of several possible segments after completing the current segment.

Suppose your generator lets you treat its 16,384-point memory as 16 1024-point segments, and suppose the generator can loop through any segment as many as 256 times. If the generator has a maximum clock rate of at least 50 MHz, you can easily use it to produce one 20-nsec-wide pulse every 16.384 msec. To produce this waveform, create one segment containing 1024 zero values and a second segment containing one full-scale value and 1023 zero values. Adjust the generator's clock to 50 MHz, and have the unit make 49 passes through the all-zeros data set, and then make one pass through the set that contains the nonzero point. The resulting waveform has none of the problems of the SFG's narrow-pulse arbitrary waveform.

True ARBs can produce fully synchronized outputs and can guarantee phase coherency when they jump to a new frequency. On the other hand, most ARBs lack the elliptic filter that SFGs use to produce sine-wave outputs. Without such a filter, an ARB cannot generate clean sine waves at almost 50% of the clock frequency. Many SFGs with 50-MHz clocks can produce 20-MHz sine waves. To produce a 20-MHz sine wave, an ARB with a typical output filter needs a clock frequency of approximately 100 MHz. Moreover, the 100-MHz ARB's 20-MHz sine wave is likely to contain more distortion than the same-frequency sine wave from the 50-MHz SFG.

The best of both worlds

Manufacturers can construct generators that combine some of a true ARB's best features with an SFG's wide frequency range and multidigit frequency resolution. These generators use DDS technology only to produce a sine wave. The sine wave is available as an output but also drives an analog comparator, which produces a square wave. Like the sine wave, the square wave is available as an output. However, the square wave also serves as a clock that drives a true ARB.

A low-cost generator that uses this architecture is Berkeley Nucleonics' new Model 625 ($995). The unit produces sine and square waves from 0 to 20 MHz with 0.1-Hz frequency resolution. The 12-bit amplitude-resolution ARB section accepts 15-bit-deep waveform records. The repetition-rate range for predefined nonsinusoidal and arbitrary functions is 0 to 2 MHz. The unit offers many modulation modes, including frequency, phase, amplitude, single sideband, phase shift keyed, binary- phase shift keyed, and frequency shift keyed. The unit also operates in swept-frequency and burst modes and produces pulses as well as standard and custom DTMF signals.

Adding jitter to waveforms

An interesting feature of some high-end true ARBs is the ability to add small amounts of jitter to output waveforms. In particular, LeCroy and Tektronix emphasize this feature (Reference 1). The peak-to-peak time jitter can be significantly less than one clock period. Surprisingly, the jitter is not the result of performing tricks with the generator's timing system. Rather, the generator simulates jitter by adding small amounts of voltage noise to the waveforms. The noise can be part of the data set that defines the waveform or can come from a separate source whose output adds to the D/A-converter output.

Suppose that a signal edge has a slew rate of 100V/µsec. Also suppose that the generator has 8-bit voltage resolution, 1V full-scale output, and a maximum clock rate of 400 MHz (2.5 nsec/clock period). The signal slews from zero to full-scale in 1/100 µsec, or four clock periods. But suppose that you want to inject jitter of 40 psec p-p, the equivalent of only ;1/60 of the clock period. In 40 psec, a signal that slews 1V at 100V/µsec slews 1/250 of full-scale, or ;1 LSB of the DAC's full- scale. Thus, if you add 1 LSB to each of the values that define one of the waveform's rising edges but add nothing to the values that define the next iteration's corresponding edge, you create the effect of 40 psec p-p of jitter.

Defining arbitrary waveforms

If you buy a waveform generator to produce waveforms that you define yourself, you will almost certainly spend more time defining and editing waveforms than generating them. You should therefore know what tools you will use to define and edit custom waveforms and be sure that your generator works well with these tools. Several generators, especially higher priced ones, incorporate extensive features for defining and editing waveforms. In fact, because their front panels sport large graphic displays, such generators look like oscilloscopes at first glance. (The generators are not scopes, though. The displays show which waveforms the units are supposed to produce, not the waveforms they actually produce.)

Some manufacturers of such generators say that their customers are more likely to use the instruments to edit waveforms than to define them. According to these manufacturers, the initial waveform definition is a task best done offline on a PC running specialized software. In Reference 2, EDN Technical Editor Bill Schweber recounts his experiences using several of the most popular packages. Although Schweber's mission was not waveform definition per se, his impressions are still valid.

Besides the mathematical software that Reference 2 discusses, nearly all manufacturers of ARBs and generators with ARB-like capabilities offer their own specialized waveform-definition packages. These mostly low-cost packages offer varied capabilities that focus more on creating and editing waveforms than on performing mathematical operations. The packages also support some popular modes that most math-software packages lack. You can capture your freehand sketches of waveforms as waveform-definition files, and you can import and edit waveforms that a digital oscilloscope or waveform digitizer has captured.

Defining in the time domain

For communications work, some packages let you specify waveforms in the frequency domain. Some even let you describe signals in the special formats of the TDMA and CDMA standards of modern digital-communications systems. Remember, though, that waveform generators are very much creatures of the time domain. A package that allows you to specify waveforms by their frequency content must still produce an output that is a function of time.

Although defining and modifying waveforms on a PC can seem convenient enough at first, don't underestimate the importance of being able to use your generator for waveform editing. As you use waveforms, "what-if" scenarios rapidly suggest themselves. If you can easily try out these cases, your experimentation will progress much more quickly. The alternative is returning to the PC, calling up the waveform definition, making changes, and downloading a new file to the generator.

One generator family that boasts particularly extensive waveform-editing capabilities is Tektronix's AWG 500 (one channel, $21,995; two channels, $28,995). These 10-bit ARBs offer clock rates to 1 GHz and memory depths to 4M samples. Tektronix recently added another high-performance ARB to its portfolio. The unit, Rohde and Schwarz's two-channel AMIQ (from $14,950) offers 14-bit voltage resolution, a 100-MHz clock rate, and a wideband-CDMA chip rate of 16.384M chips/sec. Like the AWG 500 series, the AMIQ's maximum memory depth is 4M samples.

Tektronix stresses that the presence of two series of high-performance waveform generators in its product line emphasizes the increasingly specialized nature of communications-test instruments. Rohde and Schwarz designed the AMIQ as a complement to its SMIQ RF signal generators (from $16,000), which Tek also sells. Among the AMIQ's special capabilities is its ability to null the time skew between its two channels. Differences in the cables that connect the ARB to the RF generator can introduce this skew.

Meanwhile, Hewlett-Packard boasts that the 14-bit-voltage-resolution dual-ARB, option UND ($6000) for its ESG-D series of RF-signal generators (from $14,600) requires no such adjustment. The HP waveform generator uses no external cables because it fits within the RF-signal generator.

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— Dan Strassberg, Senior Technical Editor

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