Application Note

An Introduction to Modular Arbitrary Function Generators

Electronic test and measurements equipment can be classified into two major categories; measurement instruments and signal sources. Instruments such as digital multi-meters, digitizers, oscilloscopes, spectrum analyzers, and logic analyzers measure electrical characteristics of an input signal, most typically electrical potential difference or voltage. Signal sources are required to provide signals to be used as a test stimulus. In many test situations the devices being tested do not generate signals on their own. Take for example an amplifier. Without a signal source to provide an appropriate input signal no significant electrical measurements can be made. It is the combination of measurement instruments and signal sources that make electrical testing possible. In this note we will be discussing the use of arbitrary waveform generators (AWG's), signal sources that can create test stimuli with a variety of wave shapes.

Summary of Signal Generators

There are many types of signal generators, each corresponding to specific test needs. Table 1 is a summary of commonly used generators.

Signal Source	Characteristics	Wave shape
RF signal Generators	Capable of producing CW (continuous wave) sinusoidal signals over a broad range of frequencies. Many offer various types of analog modulation. Modulation types include amplitude, frequency, phase and pulse modulation. Some variants included the ability to sweep the output frequency over a user set range for frequency response testing.	Sine Modulated sine Swept sine
Vector Signal Generators	Capable of generating digitally-modulated RF signals that may use any of a large number of digital modulation formats such as QAM, QPSK, FSK, BPSK, and OFDM.	Sine Modulated Sine
Pulse Generators	Generates pulse waveforms or square waves. Used for testing digital and pulsed systems.	Rectangular pulse
Data or Data Pattern Generators	Produce multiple logic signals (i.e. logic 1s and 0s) used as a stimulus source for functional validation and testing of digital circuits and systems.	Rectangular pulse
Function Generators	Generates simple repetitive waveforms like sine wave, saw tooth, step (pulse), square, and triangular. May include some sort of modulation function such as amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM)	Sine Rectangular pulse Square wave Triangle Ramp/saw tooth Modulated waveforms Noise
Arbitrary Waveform Generator	Digitally based signal source capable of generating any waveform, within published limits of bandwidth, frequency range, accuracy, and output level.	All the above

Table 1: A summary of commonly used signal generators

The arbitrary waveform generator comes as close as possible to being a universal signal source. Waveforms can be created analytically with great precision using equations, or captured using digitizers or digital oscilloscopes and replayed. Additionally, modular AWG's offer compact size and highly integrated compatibility with their host computers making them ideal for automated test systems.

Arbitrary Waveform Generators

Arbitrary waveform generators (AWG's) are digital signal sources that operate very much like a digitizer in reverse. Where a digitizer samples an analog waveform, digitizes it and then stores it in its acquisition memory, the AWG has a numeric description of the waveform stored in waveform memory. Selected samples of the waveform are sent to a digital to analog converter (DAC) and then, with appropriate filtering and signal conditioning, are output as an analog waveform. Figure 1 contains a conceptual block diagram of an AWG.

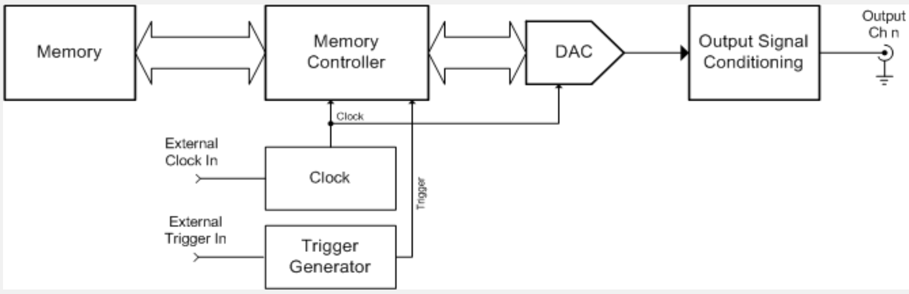

Figure 1: conceptual block diagram of an AWG

The waveform, in numeric form, is loaded into the waveform memory. Like the acquisition memory in a digitizer this memory has to be capable of being clocked at the highest sampling rate supported by the AWG. When commanded, the contents of the waveform memory are sent to the DAC where the digital values are converted into an analog voltage. Some DAC's allow additional interpolation to reach a higher update rate at the output than supplied by the waveform memory.

The memory controller keeps track of the elements of each waveform component in the waveform memory, and any associated links, and outputs them in the correct order. In addition, in order to save memory space, it can loop on repetitive elements so that these elements need be listed only once in the waveform memory.

The DAC output is harmonic rich and requires filtering. This is accomplished on the output stage which filters and conditions the signal by adjusting gains and offsets to meet the user's waveform specification.

The timing of the waveform is controlled by a clock which has provision for using an internal or an external clock source.

Synchronization is maintained by the trigger generator which causes the waveform to be output or advanced based on a user specified event. Trigger events can be internal, external, or linked to another modular AWG or digitizer.

The actual implementation of the elements above vary with specific models but all AWG's have similar elements.

Arbitrary Waveform Generator Specifications

The specifications for an arbitrary waveform generator are quite different from standard signal generators. That is due to the great flexibility in the output waveform selection and the digital nature of the AWG.

Bandwidth, Sampling Rate, and Maximum Output Frequency

The key parameters, like a digitizer, are bandwidth and sampling rate. The bandwidth determines the highest sine wave frequency that the AWG can output with a loss less than 3dB. Since many of the waveforms that can be created by the AWG are harmonic rich the bandwidth limit will determine the highest frequency waveform which can be generated. For example, a square wave generally has to be able to pass the fifth harmonic to be recognizable. For a given bandwidth the highest frequency square wave is one fifth the AWG bandwidth.

The sampling rate is related to the bandwidth. According to sampling theory the sampling rate has to be at least twice the bandwidth. With a fixed maximum bandwidth increasing the sampling rate does not improve the maximum bandwidth. The sampling rate also determines the horizontal resolution of the AWG. This defines the smallest time increment that can be set within the waveforms.

Memory Depth

The size of the waveform memory determines the longest waveform that can be output without repeating (looping) any waveform components. The limit of signal duration, without looping, is memory length times the sample period. The use of looping to repeat redundant waveform components without taking any extra memory space can greatly increase the maximum waveform length.

Modular AWG's with First-In First–Out (FIFO) streaming mode can further extend waveforms by utilizing the memory of their host computer. For example, the Spectrum M4i.66xx series products can stream data at speeds of up to 2.8 GBytes/s from the host PC to the AWG using the AWG's internal memory as a high speed buffer. This frees the AWG from the memory limits of the internal memory. Combining FIFO streaming with looping and linking functions enables the generation of an unprecedented variety of long waveforms.

Amplitude Resolution

Amplitude resolution specifies the minimum output signal level the AWG can generate and the minimum amplitude step between adjacent samples. The amplitude resolution of the AWG is determined by the number of bits of resolution of the DAC and memory. In general, there is a trade-off between DAC resolution and sampling rate. That is the greater the number of bits in the DAC the lower the maximum sampling rate.

Operating Modes

AWG's may incorporate multiple operating modes which determine how the stored waveforms are replayed. The ability to repeat (loop) selected segments of the waveform and advance between segments based on triggers or gating signals provides the ultimate is flexibility and reduces the amount of memory required for complex waveforms. Here is a summary of common operating modes:

Singleshot

The programmed waveform is played once for each external or software trigger. After the first trigger subsequent triggers are ignored.

Repeated Output

The programmed waveform is played continuously for a pre-programmed number of times or until a stop command is executed. The trigger source can be either an external trigger inputs or the software trigger. After the first trigger additional trigger events will be ignored.

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Single Restart Replay

This mode outputs the waveform data of the on-board memory once after each trigger event. The trigger source can be either an external trigger or the internal software trigger.

FIFO

The FIFO mode is an operating mode unique to Spectrum's modular AWG's. It is designed for continuous data transfer between the host computers memory or hard disk and the AWG. The control of the data stream is done automatically by the driver on an interrupt request basis. The complete installed on-board memory is used for buffering data, making the continuous streaming extremely reliable.

Multiple

The Multiple Replay mode provides fast output of waveforms on multiple trigger events without restarting the hardware. The on-board memory is divided into several equal size segments. Each segment can contain different waveform data, each of which is output with the occurrence of each trigger event. This mode allows very fast repetition rates.

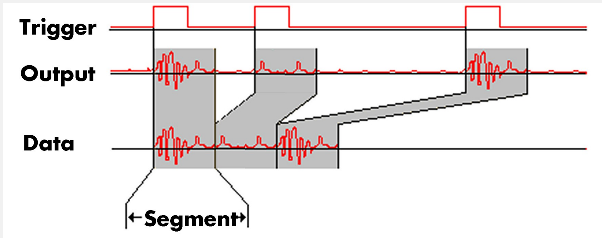


Figure 2: AWG Multiple Replay Output

Gated Replay

The Gated Replay sampling mode outputs waveform data controlled by an external gate signal. Data is only replayed if the gate signal is at a pre-programmed level.

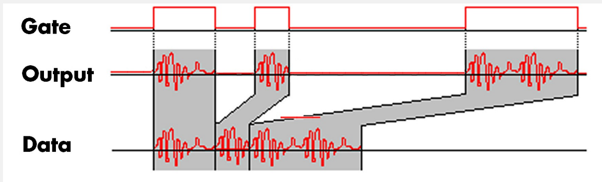


Figure 3: AWG Gated Replay Mode

Sequence Mode

The sequence mode splits the internal card memory into a number of data segments of different lengths. These data segments are chained in a user set order using an additional sequence memory. The sequence memory determines the order that segments are output as well as the number of loops for each segment. Trigger conditions can be defined to advance from segment to segment. It is possible, in sequence mode, to switch between replay waveforms by a simple software command or to redefine waveform data for segments simultaneously while other segments are being replayed.

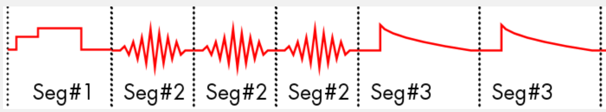


Figure 4: AWG Sequence Mode

Output Amplitude Range

The maximum output amplitude that the AWG can generate is determined by the output amplifier stage. In general, there is also a trade-off between an AWG's sampling rate and output amplitude with faster AWG's having a lower maximum output amplitude. The minimum full scale output range depends on the internal attenuators in the output stage. On any given full scale range the theoretical minimum value is the full output divided by the amplitude resolution (e.g. an AWG with a 10 Vp-p range and 16 bit resolution has a minimum output step of 10/65,536 = 152.5 µV). Internal noise and non-linearity limit the practical minimum signal output.

Number of Output Channels

The number of output channels per card for Spectrum AWG's can be 1, 2, or 4 channels. Using multiple cards and the Spectrum Star-Hub up to 8 cards can be linked offering a maximum of 32 fully synchronized channels.

Output Filtering

Output filtering improves the signal to noise ratio of the AWG output. Generally the types and cutoff frequencies of the filters can be specified.

Modulation

All AWG's can create modulated waveforms by creating them analytically, in software, using manufacturer's operating software like Spectrum's SBench 6 or other third party math software, and downloading them into the AWG's waveform memory.

Triggering

Another useful feature is having a trigger input to initiate the output or to advance the waveform through multiple segments.

AWG's can also produce an output trigger or marker output synchronous with the waveform output. These signals can then be used to trigger a digitizer, oscilloscope, or other instrument at appropriate times during the waveform.

Digital Outputs

Some AWG's can produce parallel digital logic outputs in addition to analog outputs. These digital outputs are normally added to the waveform data either by reducing the analog resolution or by placing them in unused bits of the data word (like a 14 bit AWG having two spare bits in the 16 bit data word). . The output levels are typically those of common logic families.

Selecting an Arbitrary Waveform Generator

The selection of an AWG requires matching the AWG specifications discussed earlier with the test specification.

- **Bandwidth:** The basic starting point is generally the bandwidth of the AWG which determines the highest frequency that can be output. This must be greater than or equal to the maximum frequency required for testing. Keep in mind that harmonic rich waveforms require bandwidths three to five times the frequency required.

- **Sampling rate:** The maximum sampling rate of the AWG must be at least twice the required bandwidth. This is the Nyquist limit and, in practice, it is generally better to over sample by a factor of three or four. The sampling rate determines the smallest increment of time that can be programmed. Note that AWG's often restrict the minimum number of samples required to create a waveform. Generally they require waveforms to contain an even number of samples or be multiples of a fixed number of samples (e.g. 4, 8, 16, etc.).

- **Memory Length:** The waveform memory length determines the longest duration, non-repeating signal that the AWG can support. Operating modes that support ‘looping’ or repeating redundant elements in the waveform decrease the amount of waveform memory required.
  The FIFO operating modes, which use the host computers memory, provide a method for increasing the available memory.

- **Output Amplitude:** The maximum output level of the AWG must match the test requirement. If not, it may require an external amplifier with a bandwidth equal to or exceeding the AWG’s.

- **Dynamic Range/Amplitude Resolution:** The ratio of the highest test signal amplitude to the minimum amplitude at the same time determines the dynamic range requirements of the test. This is determined by the amplitude resolution of the AWG expressed in bits. Note that noise and non-linearity in the AWG limit the dynamic range to less than the theoretical values. The actual performance is often characterized as the effective number of bits (ENOB).

Typical Modular AWG’s

Table 2 provides a summary viewing of Spectrum’s PCIe modular AWG’s.

Model	Number of Channels	Resolution	Maximum Sampling rate	Bandwidth	Maximum Output into 50 Ω	Standard Memory	Maximum Memory
M2i.6011	2	14 Bit	20 MS/s	10 MHz	±3 V	256 MS	1 GS
M2i.6012	4	14 Bit	20 MS/s	10 MHz	±3 V	256 MS	1 GS
M2i.6021	2	14 Bit	60 MS/s	30 MHz	±3 V	256 MS	1 GS
M2i.6022	4	14 Bit	60 MS/s	30 MHz	±3 V	256 MS	1 GS
M2i.6030	1	14 Bit	125 MS/s	60 MHz	±3 V	256 MS	1 GS
M2i.6031	2	14 Bit	125 MS/s	60 MHz	±3 V	256 MS	1 GS
M2i.6033	1/2	14 Bit	125/62.5 MS/s	60 MHz	±3 V	256 MS	1 GS
M2i.6034	2/4	14 Bit	125/62.5 MS/s	60 MHz	±3 V	256 MS	1 GS
M4i.6620	1	16 Bit	625 MS/s	200 MHz	±2.5 V	2 GS	2 GS
M4i.6621	2	16 Bit	625 MS/s	200 MHz	±2.5 V	2 GS	2 GS
M4i.6622	4	16 Bit	625 MS/s	200 MHz	±2.5 V	2 GS	2 GS
M4i.6630	1	16 Bit	1250 MS/s	400 MHz	±2 V	2 GS	2 GS
M4i.6631	2	16 Bit	1250 MS/s	400 MHz	±2V	2 GS	2 GS

Table 2: Summary Table of Spectrum AWG’s

These AWG’s are all PCIe based modules providing high volumetric efficiency with high performance. Sampling rates run from 20 MS/s to 1.25 GS/s with simultaneous bandwidths from 10 to 400 MHz. Maximum on-board memory lengths are from 256 MS to 2 GS, well above typical benchtop instruments.

The latest additions, the M4i.66xx series are based on the PCIe-x8 platform and can stream data from the host PC to the card at rates up to 2.8 GB/s. Combining the fast interface with FIFO modes extend the maximum memory available to the limits of the host computer. In FIFO mode the 2 GS on-board memory is used as a buffer providing a ‘gap-less’ interface.

Sequence mode operation offers dynamic, on the fly, looping and linking resulting in infinite variations in test patterns.

Software Support

The AWG requires software for waveform generation and operational control. Almost all AWG’s are shipped with drivers for common operating systems. In the case of the Spectrum AWG’s drivers for Windows and Linux are supplied. Drivers allow you to write your own software using common programming languages like C/C++, IVI, .NET, Delphi, Visual Basic, and Python. Drivers also support third party software such as LabVIEW (Windows), MATLAB (Windows and Linux), and LabWindows/CVI. Spectrum also includes a full featured software package called SBench 6.

SBench 6 is a powerful and intuitive interactive measurement software for acquiring, processing, and creating signals. It is designed to work with all Spectrum’s digitizers, AWG’s, and LAN based digitizerNETBOX systems.

Easy Generator

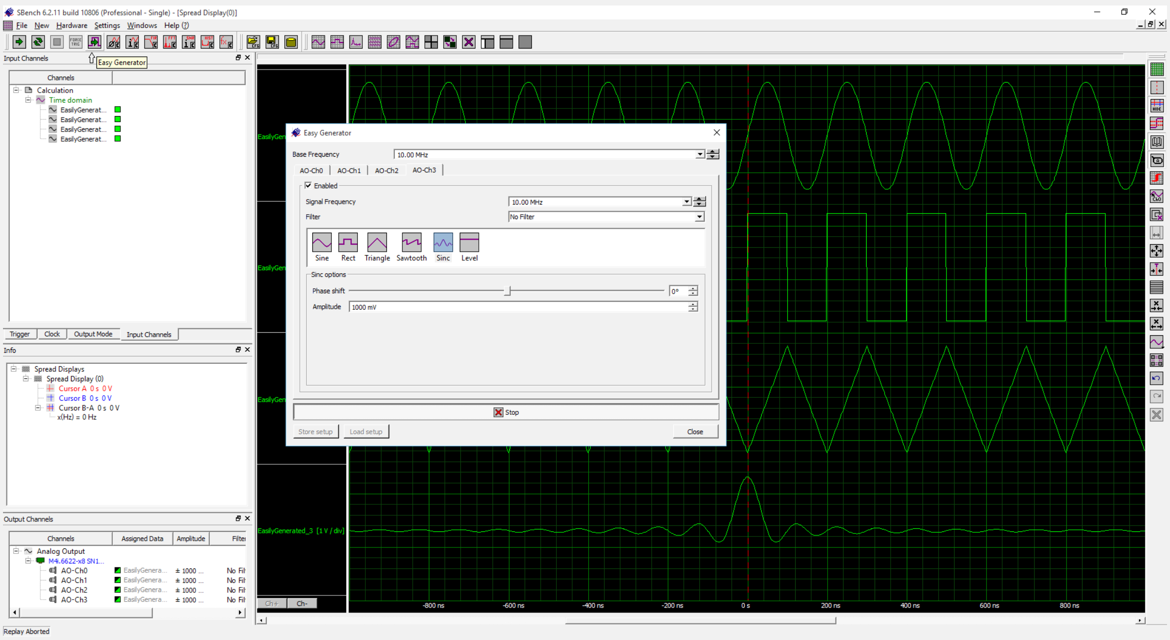


Figure 5: The SBench 6 Easy Generator tool allows to operate the AWG as simple signal generator

One of the components of SBench 6 is the Easy Generator tool. Easy Generator facilitates the selection of any of six function generator waveforms including sine, rectangular, triangle, saw tooth, SINC, and DC waveforms. The frequency, phase, and amplitude of each waveform is user adjustable, as is the duty cycle for the rectangular, triangle and saw tooth waveforms. Individual waveform setups can be selected for each available output channel and a simple press of the Start button transfers all enabled waveforms to the AWG outputs as shown in Figure 5.

Creating Waveform Using Equations in SBench 6.

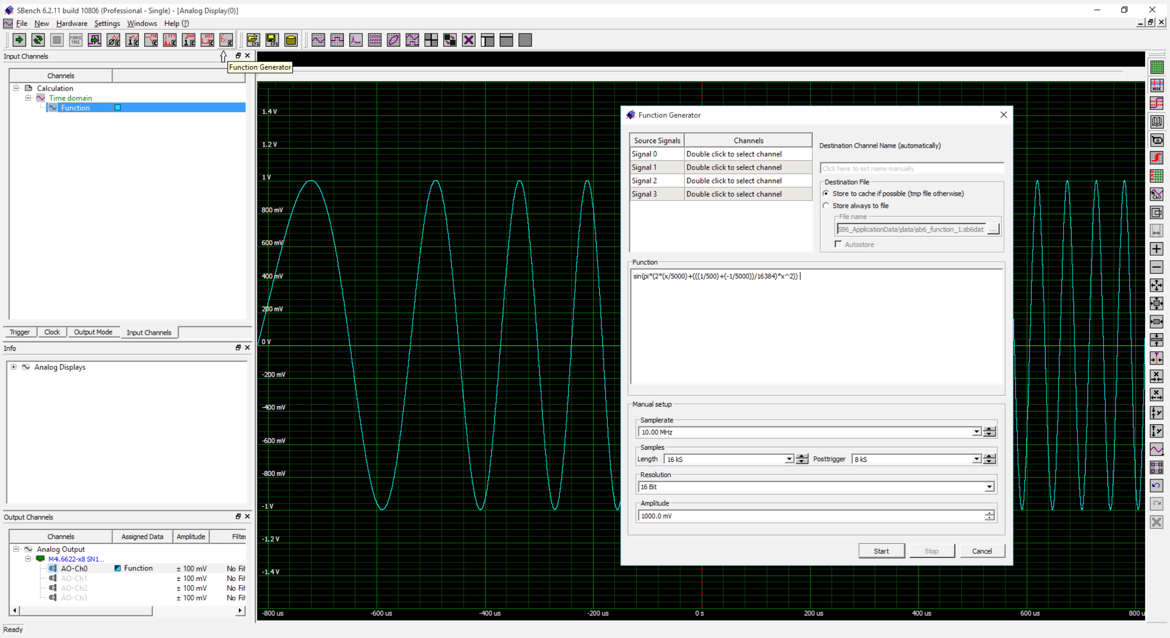


Figure 6: Generating AWG output data by using SBench 6 mathematical equations

The most accurate way to create waveforms is to base them on mathematical equations. They are precise and repeatable and offer a great range of test signals. SBench 6 includes a function generator editor which supports the generation of waveforms using text based equations as shown in Figure 6.

The function generator editor accepts the equation in text format and allows for the selection of the sampling rate, amplitude, and duration of the waveform.

Figure 7 shows a more detailed example of creating the sine sweep waveform using the operators and functions available in SBench 6.

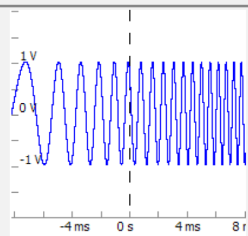
Linear Frequency Sweep	Sin(pi*(2*(x/X_S)+(((1/X_E)-(1/X_S))/X_{MAX})*x^2)) X_S – Start Period in samples X_E – End Period in samples X_{MAX} – Duration of the waveform in samples Example: sin(pi*(2*(x/5000)+(((1/500)+ (-/5000))/16384)*x^2))	

Figure 7: Generating a sine sweep using SBench 6 equations

Importing Waveforms

Waveforms can be created locally in Spectrum's SBench 6 software, as we have seen. Waveforms can also be created or acquired from other sources including instruments like digitizers and digital oscilloscopes and software tools like spreadsheets, math programs, and system integration software. Waveforms from these sources can be imported into SBench 6 and sent to the AWG using any of the formats listed in Table 3.

Waveform Source	File Format for transfer
Spectrum Digitizer	.sb6dat, ASCII, Binary
Spectrum AWG	.sb6dat, ASCII, Binary
Spectrum digitizerNETBOX	.sb6dat, ASCII, Binary
Digitizer (Non-Spectrum)	ASCII, Binary, Wave
Digital Oscilloscope	ASCII, Binary, Wave
Spreadsheet (Excel)	ASCII
Math Program (MATLAB)	ASCII, Binary
System Integration Software (LabVIEW)	ASCII, Binary
Audio Recording	.WAV

Table 3: Typical waveform sources and the data formats supported by SBench 6

Applying Signal Processing to Waveforms

SBench 6 offers a number of signal processing and measurement tools that can be applied. Multiple waveforms can be combined using waveform arithmetic which supports sum, difference product and ratio. Moving average and filtering can be used to reduce noise and improve the signal to noise ratio. Analysis tools like the Fast Fourier transform (FFT) and histograms can be used to investigate the waveform before being output. Measurements of amplitude, time and frequency can be used to confirm waveform accuracy. This is a very unique capability available in an AWG support software package.

Conclusion

Modular arbitrary function generators are excellent signal sources for test systems providing small size, configuration flexibility, and easy integration. With bandwidths of up to 400 MHz, sampling rates to 1.25 GS/s and with 16 bits of amplitude resolution they offer a broad range of test solutions.

Authors

Arthur Pini – Independent Consultant
Oliver Rovini- Technical Director, Spectrum GmbH
Greg Tate - Asian Business Manager, Spectrum GmbH

