The basic output waveform and related parameters of the arbitrary waveform generator

Traditional function generators can output standard waveforms such as sine waves, square waves, and triangle waves. However, in actual test scenarios, in order to simulate the complex conditions of the product in actual use, it is often necessary to artificially create some "irregular" waveforms or add some specific distortion to a waveform. Traditional function generators can no longer meet the requirements and an arbitrary waveform generator may be a good option.

Arbitrary waveform generators can easily replace the function generators. They can source sine waves, square waves, and triangle waves like a standard function generator. In addition, they can also output pulse, noise, DC signal types, modulated signals, sweeps and bursts. Many arbitrary waveform generators currently on the market are equipped with arbitrary waveform drawing software. Through this software, theoretically, the arbitrary waveform generator can be remotely controlled to output all the signals required in the test process.

So, what types of waveforms can an arbitrary waveform generator output?
What parameters are available for an arbitrary waveform?
How to measure the quality of the output waveform?

1. Sine Wave / Cosine Wave

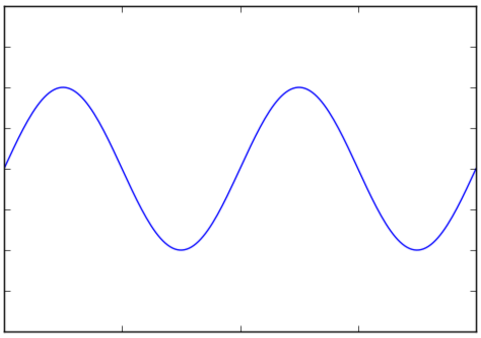


Figure 1 Sine wave / Cosine wave

Sinusoidal (sine) and cosine waves are the two most familiar waveforms in electronics.
Sine/cosine waves are defined as follows.

$$f(t) = A\cos(\omega_c t + \phi_0) \quad \text{(Formula 1)}$$

OR

$$f(t) = A\sin(\omega_c t + \phi_0) \quad \text{(Formula 2)}$$

Where A represents the amplitude of the sine wave, ω_c represents the angular frequency, and ϕ_0 represents the initial phase, which can be omitted in the general calculation. The sine and the cosine waves are essentially the same, but the initial phase differs by 90 °.

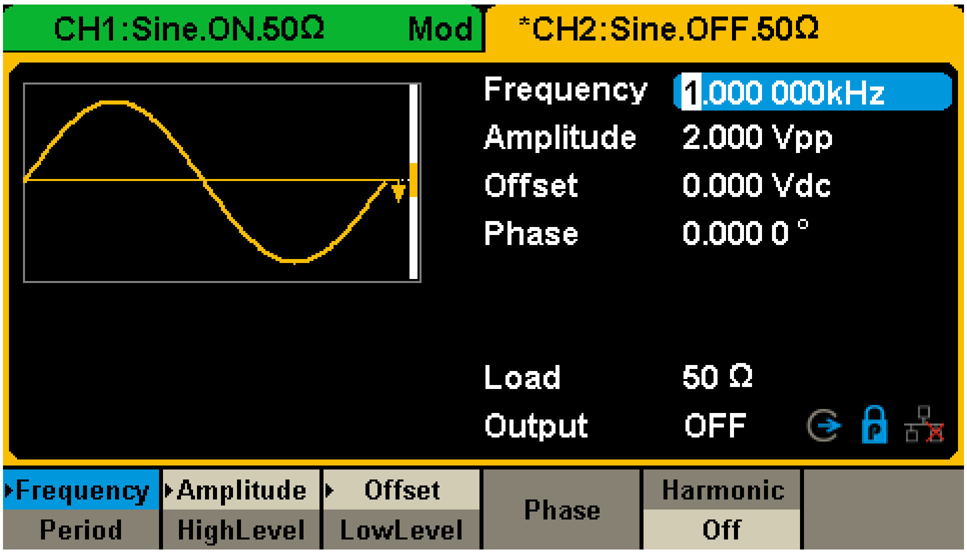


Figure 2 Sine wave setting interface in SDG1000X

These three parameters are as shown in Figure 2. The frequency and period related to the angular frequency can be set in the arbitrary waveform generator, and the conversion relationship between them is:

$$f = \frac{1}{T} = \frac{\omega}{2\pi}$$ (Formula 3)

The frequency of a generator, like the SIGLENT SDG2122X function / arbitrary waveform generator sine wave can be set up to 120 MHz. Usually, the nominal maximum output frequency of the arbitrary waveform generator often refers to the maximum frequency of its sine wave output.
You can also set the amplitude, A. When the output impedance is set to the "high impedance" state, the maximum output amplitude of the SDG2122X can reach 20 Vpp.

The initial phase can be set by clicking the corresponding button in the [Phase] menu. The range of the initial phase can be set between -360 ° and + 360 °.

From the time domain perspective, the parameters and waveforms of the sine and cosine waves are relatively simple. However, all electronic devices have more or less distortion, and arbitrary waveform generators are no exception. Let’s observe sine and cosine waves in the frequency domain.
The Fourier transform corresponding to the time domain function represented by Formula 1 is:

$$F(\omega) = \pi \cdot \left[\delta(\omega - \omega_c) + \delta(\omega + \omega_c)\right] \quad \text{(Formula 4)}$$

The spectrum diagram represented by Formula 4 is shown in the figure below:

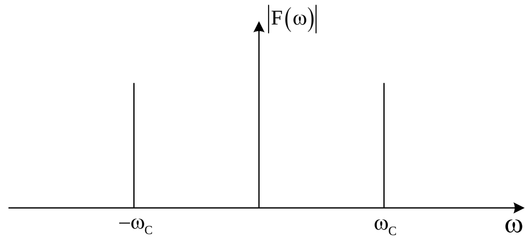


Figure 3: Cosine spectrum/frequency domain

Looking at the cosine spectrogram (showing amplitude vs. frequency) in Figure 3, we can find that the frequency of a sine/cosine wave can be represented by a single line on the spectrum. Signals that occupy only one frequency are called "monotone" because they only have one frequency component.

In engineering, due to the non-ideal characteristics such as the non-linearity of the circuit, the generated sine wave is often not an ideal monotone signal, but may contain other frequencies. Collective "unwanted" frequencies are often lumped together under the term distortion. Some common contributors to distortion are harmonics and spurs.

1.1 Harmonic distortion

The fundamental frequency of a signal is the lowest frequency component of a periodic signal. Harmonics are the frequency components of the signal that are integer multiples of the fundamental. Distortion is the ratio of signal power to maximum harmonic power, usually in dB, as shown in the following figure:

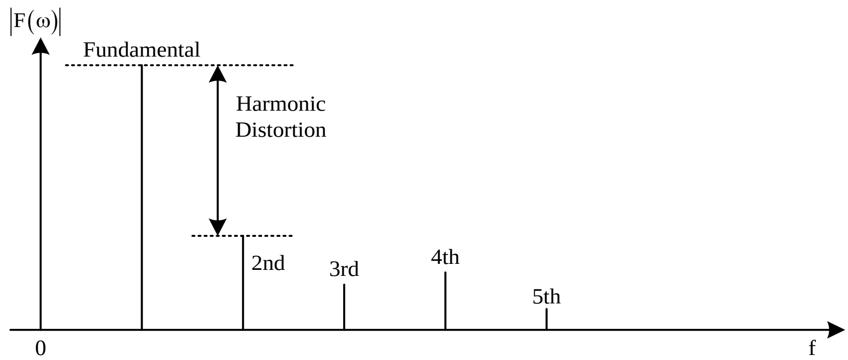


Figure 4: Harmonic distortion

Another index to measure the performance of harmonic distortion is total harmonic distortion (THD), which refers to the ratio of the root mean square of the amplitude of each harmonic (usually taken to the 6th harmonic in engineering) to the signal amplitude, as shown in Formula 5, usually expressed in %. When an SDG2000X outputs 0 dBm, 10 Hz ~ 20 kHz sine wave, the total harmonic distortion is 0.075% at most.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_s}$$

(Formula 5)

1.2 Non-harmonic spurs

In addition to harmonics, the distortion caused by nonlinearity may also be some other spectral components, such as the intermodulation products of the signal (or its harmonics) and the clock signal. It is necessary to define other index-non-harmonic spurs to measure.

The size of the spur is usually expressed by the spurious-free dynamic range (SFDR) (see Figure 5), which refers to the ratio of the signal power to the maximum spurious power. The unit is usually dB. Please note that the definition of spurs in some places includes harmonic and non-harmonic spurs, but in arbitrary waveform generators, spurs only refer to distortions other than harmonics.

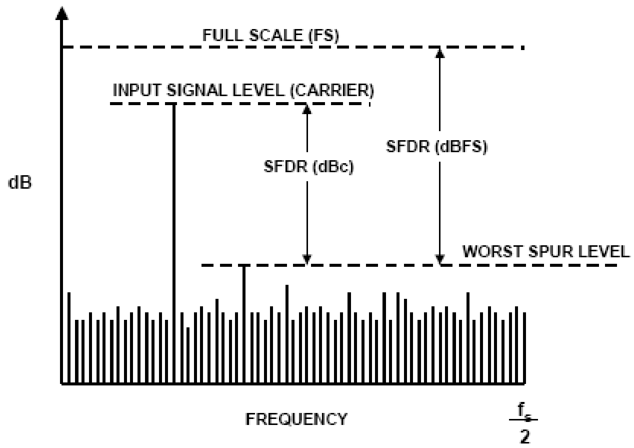
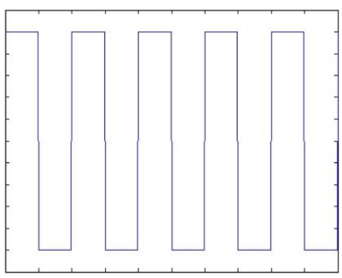


Figure 5: SFDR

2. Square Wave / Pulse



Square wave / pulse

The time-domain waveform of the square wave can be represented by the following diagram:

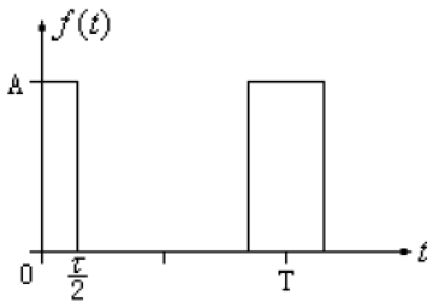


Figure 7 Square wave time domain diagram

The expression of the square wave in a period is:

$$f_T(t)=\begin{cases}0, & -\frac{T}{2}\le t<-\frac{\tau}{2},\\ A, & -\frac{\tau}{2}\le t<\frac{\tau}{2},\\ 0, & \frac{\tau}{2}\le t\le\frac{T}{2}\end{cases}$$ (Formula 6)

T is the period of the square wave and the length of time occupied by the high level in a period. It is the duty cycle of the square wave.

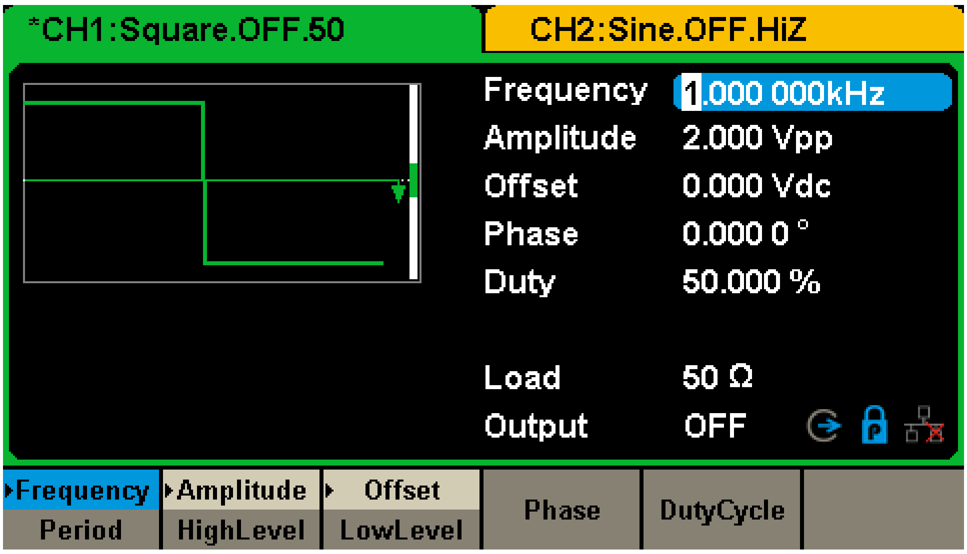


Figure 8 SDG2000X square wave setting interface

In the square wave setting interface, in addition to setting all the parameters that can be set by the sine wave / cosine wave, the option of setting the duty cycle is added, but in the arbitrary waveform generator, the setting range of the duty cycle is generally affected by the frequency Set limits. Formula 6 is actually a rectangular function, and its frequency spectrum can be expressed as:

$$F_T(\omega) = \frac{2A}{\omega}\sin\frac{\omega\tau}{2} = A\tau \cdot \mathrm{sinc}\left(\frac{\omega\tau}{2}\right) \text{(Formula 7)}$$

This is a sinc function with amplitude $A\tau$.

Since the square wave is an extension of the rectangular function taking T as the period, we can use some digital signal processing theories to further our point.

A function is periodic in the time domain, corresponding to the discretization in the frequency domain, therefore, the spectrum of the square wave is actually the spectrum is $F_T(\omega)$ sampled with $\omega = n\frac{2\pi}{T}, n \in Z$ as the sampling point. Intuitively, it is the angular frequency ω_1 of the square wave and its harmonic components under the envelope of the sinc function.

The following figure is the spectrum corresponding to the square wave of amplitude A, $T = 5\tau$, where ω_1 is the fundamental frequency of the square wave:

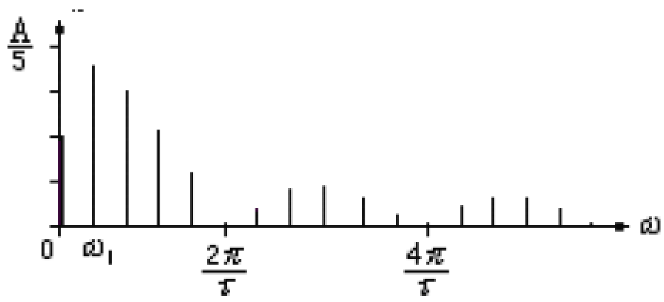


Figure 9 Square wave spectrum

It can be seen that the spectrum of the square wave is infinitely wide. If you let the square wave pass through a low-pass filter and only retain some of its harmonic components, the waveform in the corresponding time domain will be distorted. As can be seen from the figure below, the square wave after low-pass filtering not only slows down the signal edge, but also produces an overshoot up and down. This overshoot phenomenon is the "Gibbs effect".

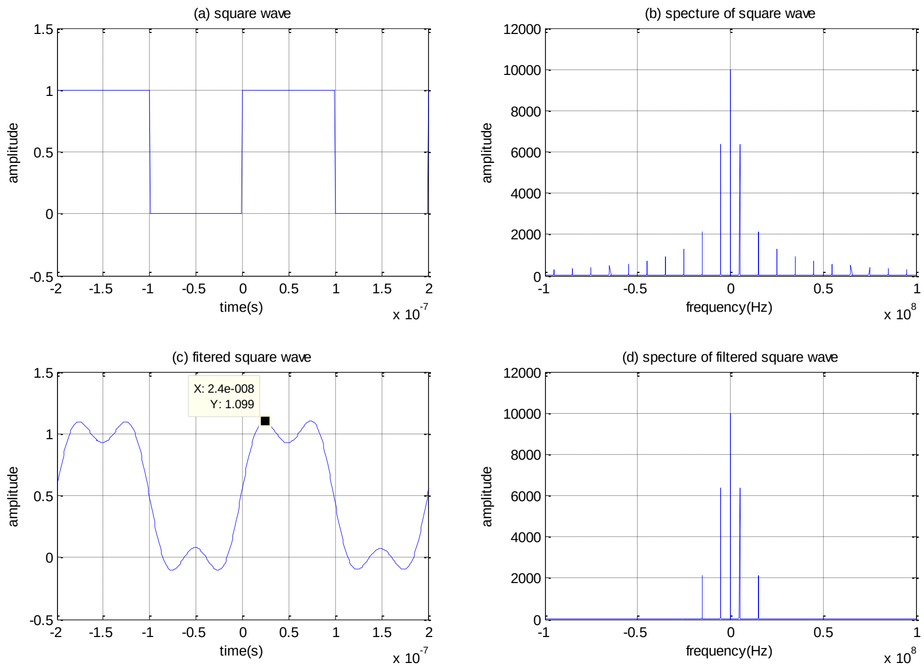


Figure 10 5 MHz square wave, 50% duty cycle, 3rd harmonic reserved

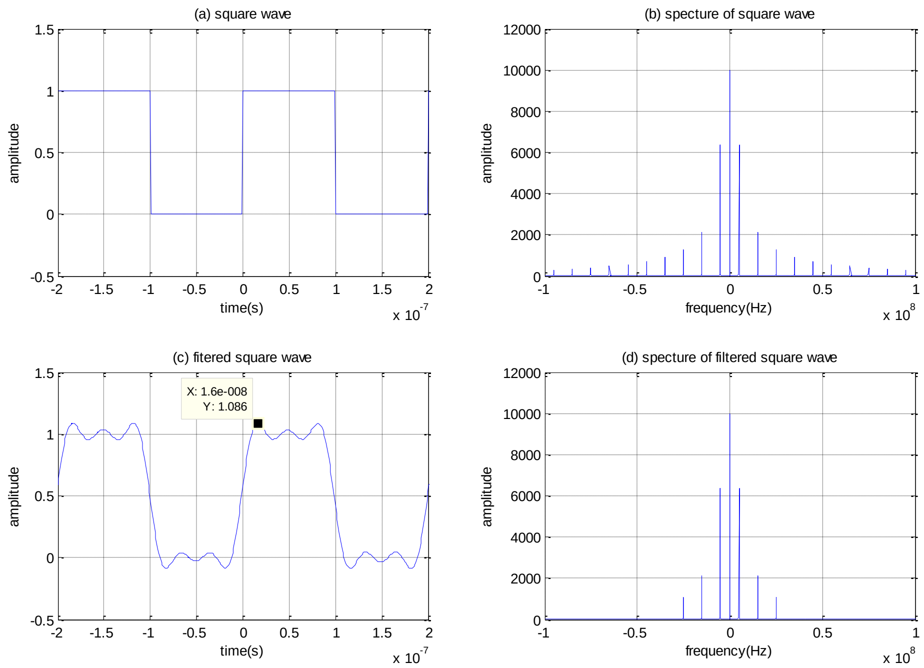


Figure 11 5 MHz square wave, 50% duty cycle, 5th harmonics reserved

More harmonics can mean less distortion for square waves. For narrow pulses, due to the wide spread of the Sinc function envelope and the spread of spectrum energy, it is often necessary to retain many orders of higher harmonics to avoid large distortions. As shown in the figure below, it is also the 5 MHz frequency, which retains the 5th harmonic, but the narrow pulse of 20 ns has already distorted in amplitude.

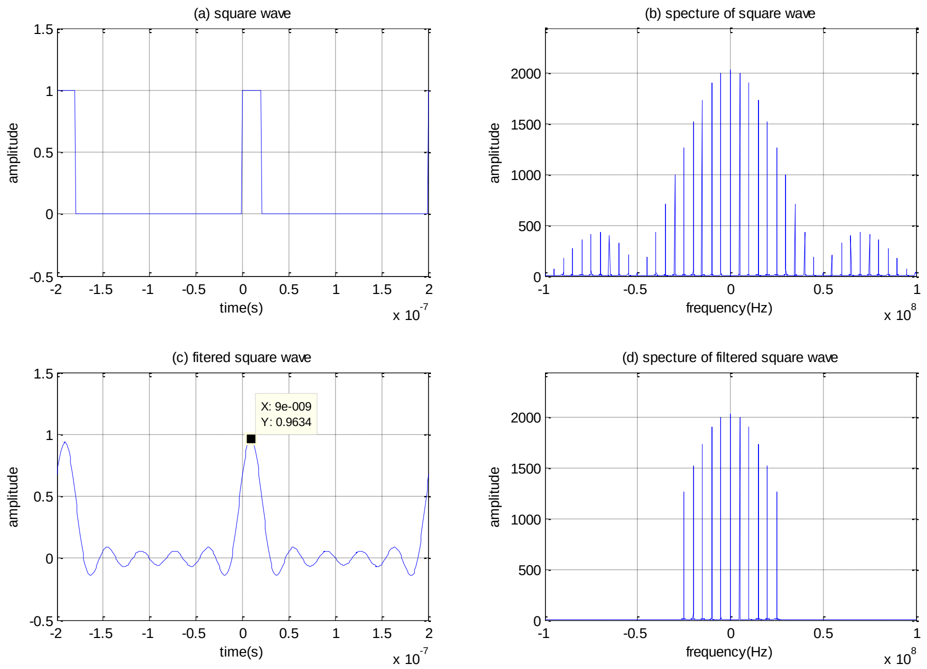


Figure 12 5 MHz pulse, 20 ns, 5th harmonic reserved

For a square wave with a 50% duty cycle, at least the 3rd to 5th harmonics must be retained for decent reproduction. Therefore, the square wave frequency of the arbitrary waveform generator generally cannot reach its maximum output frequency index. This can be verified on the generator datasheet.. such as SDG5000 function / arbitrary waveform generator series, were the maximum output sine frequency is 160 MHz, but the maximum frequency of a square wave is 50 MHz.

2.1 Jitter

Square wave / pulse is often used as a clock signal, so we must pay attention to the clock signal – jitter specification. Jitter can be defined as the deviation of a signal from its ideal time position when it transitions.

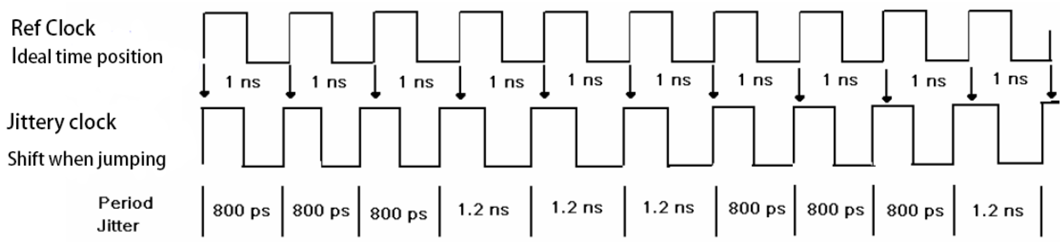


Figure 13 period jitter

The components of a signal jitter are complicated, mainly divided into deterministic jitter and random jitter. Random jitter displays a Gaussian distribution while deterministic jitter is composed of multiple components. For example, in an arbitrary waveform generator, the square wave / pulse generated by the DDS method may produce deterministic jitter of 1 sampling period. Many generators use a unique design known as EasyPulse technology to eliminate this jitter. We will expand on EasyPulse technology in the following chapters.

There are usually three ways to measure jitter in the time domain: Period, cycle-cycle and TIE. The method we use when measuring jitter is cycle-cycle. Since the components of jitter contain random components that have a Gaussian distribution, the root mean square value (rms) is generally used to measure the jitter according to statistical methods.
The SDG2000X series function / arbitrary waveform generator using EasyPulse technology has a jitter specification of < 150 ps, which effectively overcomes the larger jitter seen with other designs that use only Direct Digital Synthesis (DDS) technology.

3. Triangle Wave

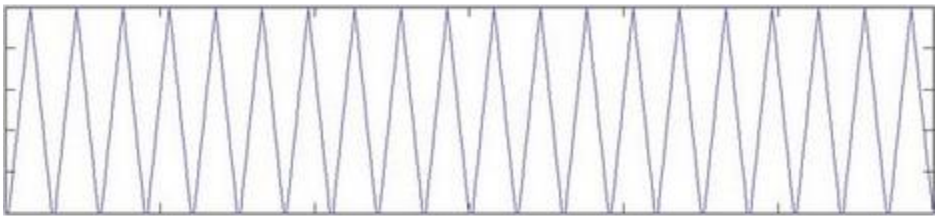


Figure 14 Triangle wave

The time-domain waveform of a triangular wave with 50% symmetry is shown in the figure below:

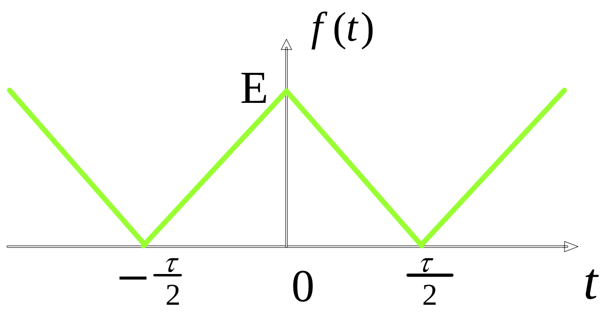


Figure 15: Triangular wave time domain waveform

The mathematical expression of a triangular wave with a period τ in a period is as follows, we call it a triangular pulse:

$$f_T(t) = E(1 - \tfrac{2}{\tau}|t|) \quad (|t| < \tfrac{\tau}{2})$$ Formula 8

The corresponding spectrum expression is:

$$F_T(\omega) = \frac{E\tau}{2}\sin c^2(\frac{\omega\tau}{4})$$ （Formula 9)

Similar to the square wave, the triangle wave is an extension of the triangle pulse with T= τ as the period, so the spectrum of the triangle wave is actually the spectrum is $F_T(\omega)$ sampled with $\omega = n\frac{2\pi}{T} = n\frac{2\pi}{\tau}, n \in Z$ as the sampling point. Intuitively, it is the angular frequency ω_1 of the square wave and its harmonic components under the envelope of the sinc function. The corresponding spectrogram is as follows. It can be seen that since the square envelope of the Sinc function is equal to 0 when n is even, the triangle wave spectrum actually contains only odd harmonics.

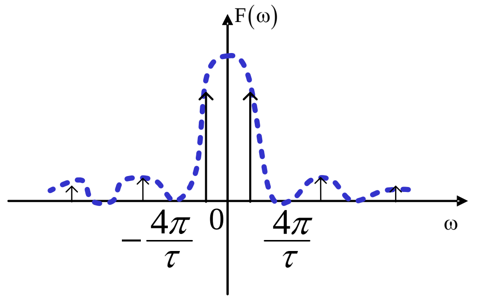


Figure 16 Triangle wave spectrum

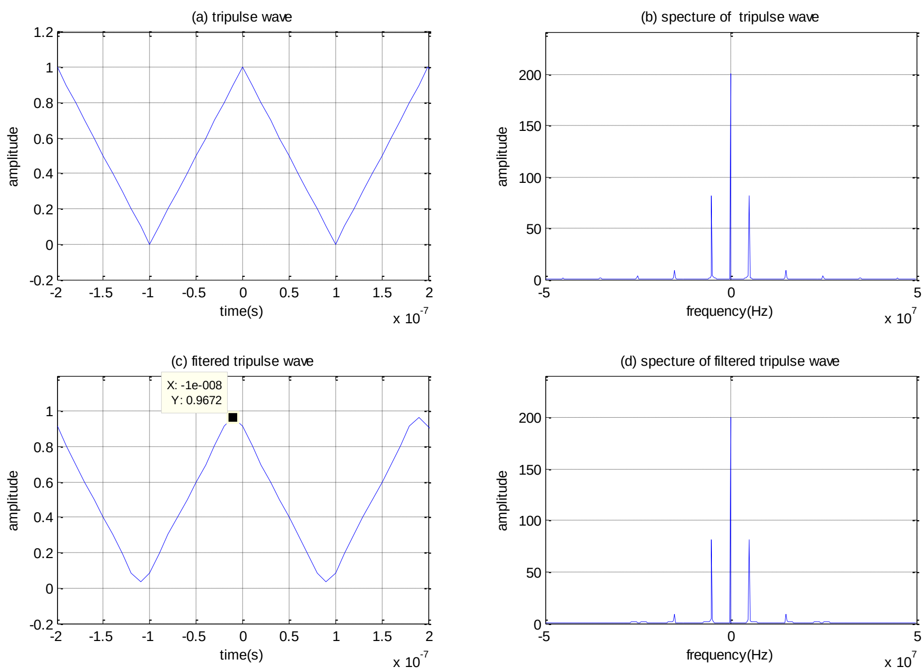


Figure 17 5 MHz triangle wave, after 20 MHz low-pass filtering

In the triangle wave setting interface, you can set the symmetry of the triangle wave. The setting range is from 0% to 100%. When the value of the symmetry is not 50%, the arbitrary waveform generator will output a sawtooth wave.

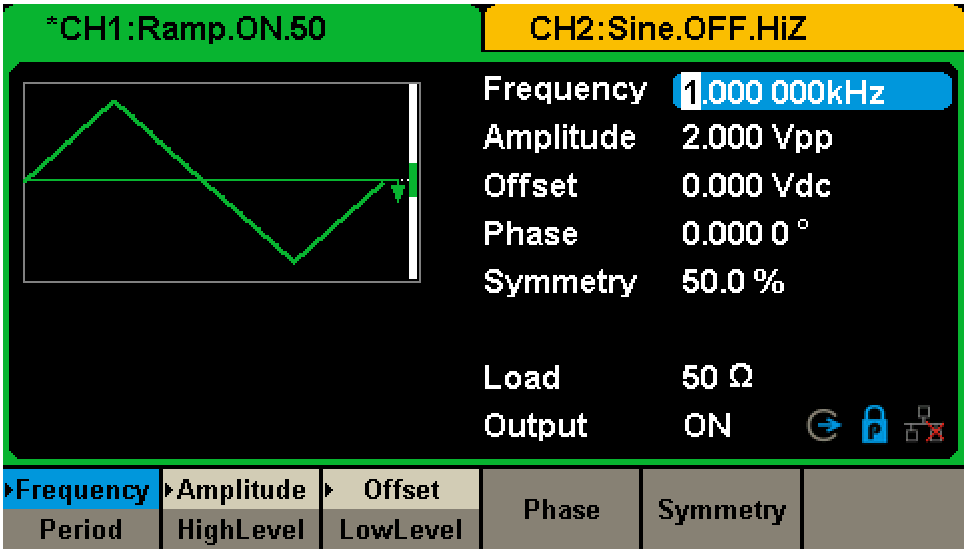


Figure 18 Triangle wave parameter setting interface

4. Sawtooth Wave

The sawtooth wave is an "asymmetric triangular wave". In the most extreme case, the symmetry is even 0% or 100%. At this time, the sawtooth wave has a jump in the time domain, and the spectrum on the corresponding spectrum will be wide. Similar to narrow pulses, many higher order harmonics must be retained to insure less distortion.

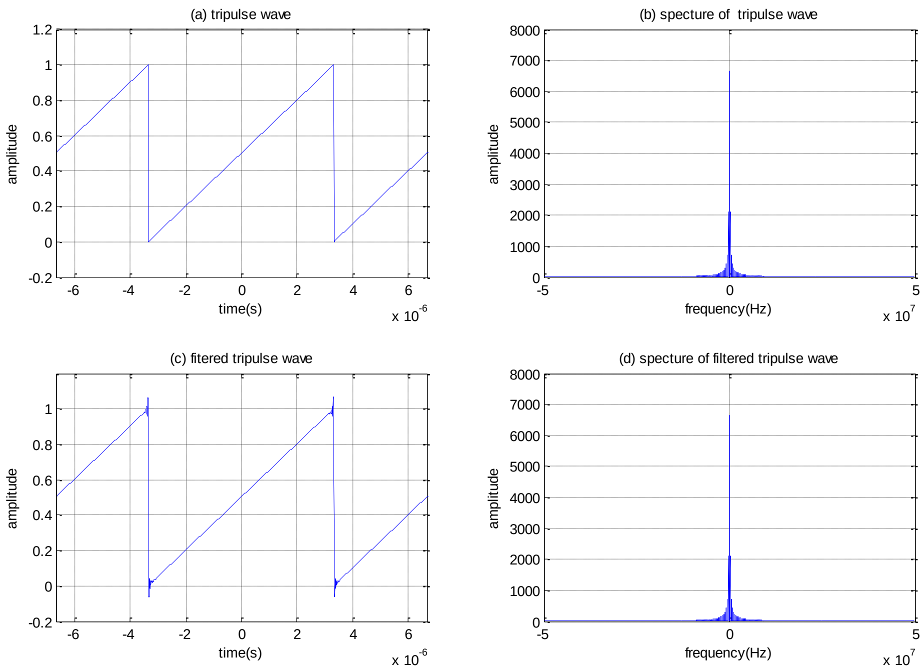


Figure 19 150 kHz sawtooth wave, after 20 MHz low-pass filtering

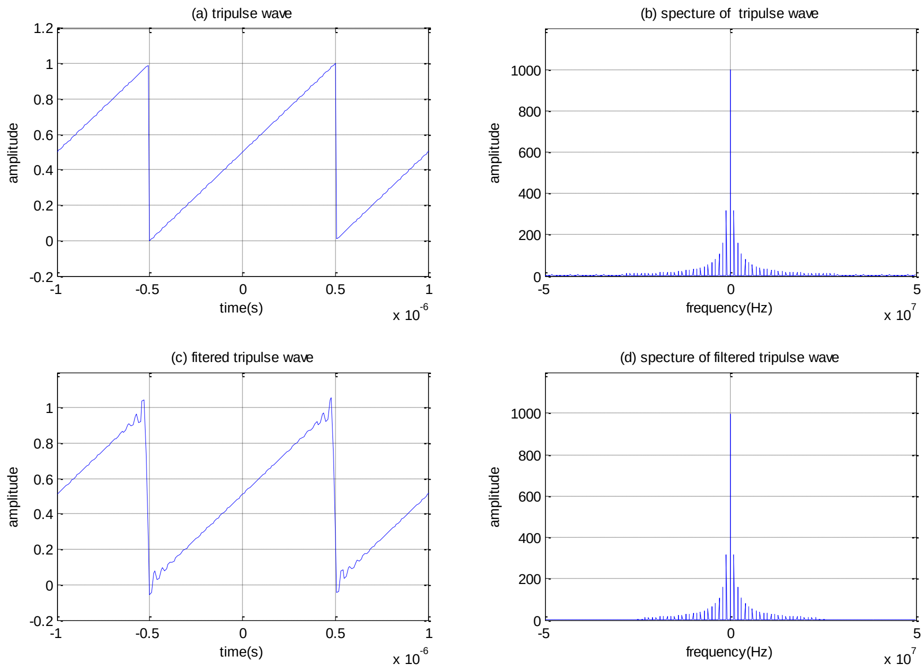


Figure 20 1 MHz sawtooth wave, after 20 MHz low-pass filtering

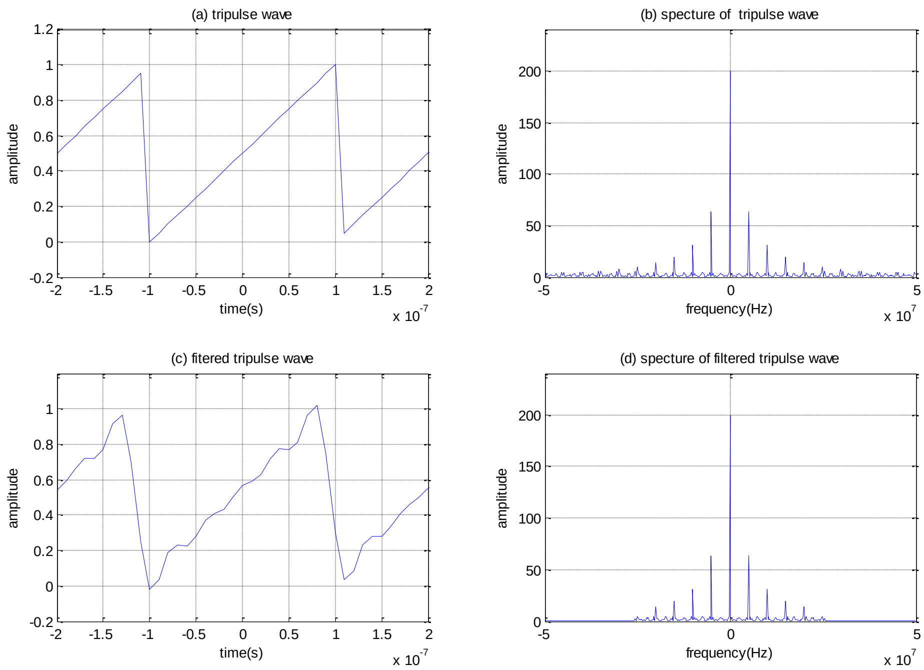


Figure 21 5 MHz sawtooth wave, after 20 MHz low-pass filtering

5. White Gaussian Noise

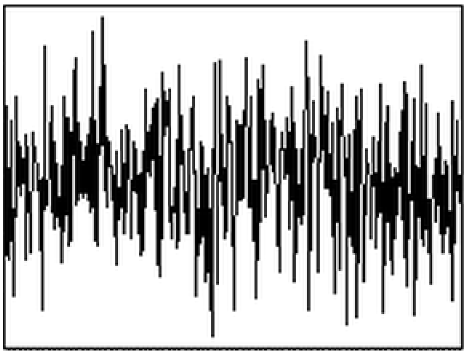


Figure 22　　Noise

If the amplitude distribution of noise obeys a Gaussian distribution and its power spectral density is uniformly distributed, it is called white Gaussian noise. Natural thermal noise, quite commonly the largest noise source in electronics, is white Gaussian noise.

The amplitude of Gaussian noise is a random number, not a certain value. So we use two statistical parameters of the Gaussian distribution: mean (μ) and standard deviation (σ) to measure the magnitude of Gaussian noise.

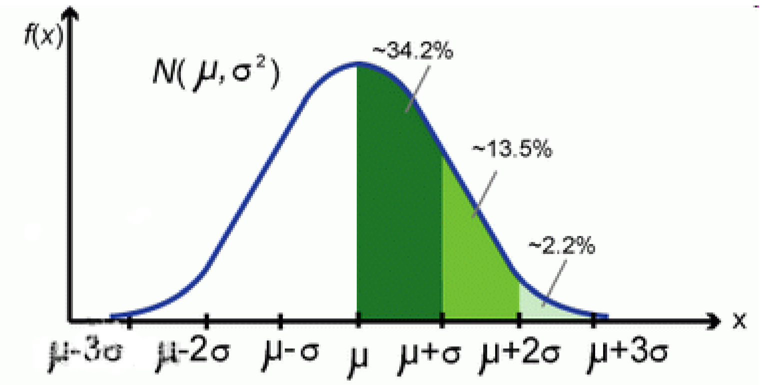


Figure 23: The mean and standard deviation of Gaussian noise

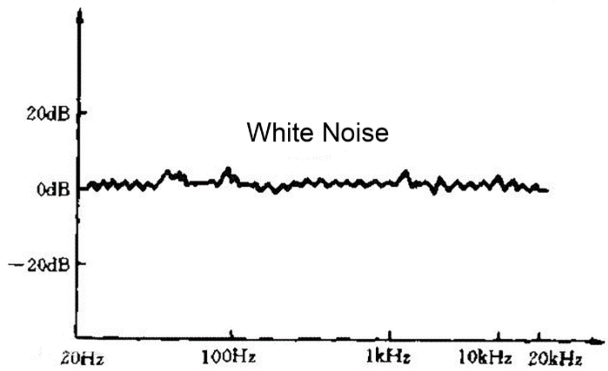


Figure 24: White noise power spectrum

In many SIGLENT arbitrary waveform generators, you can set the two parameters of the average and standard deviation of the output noise.

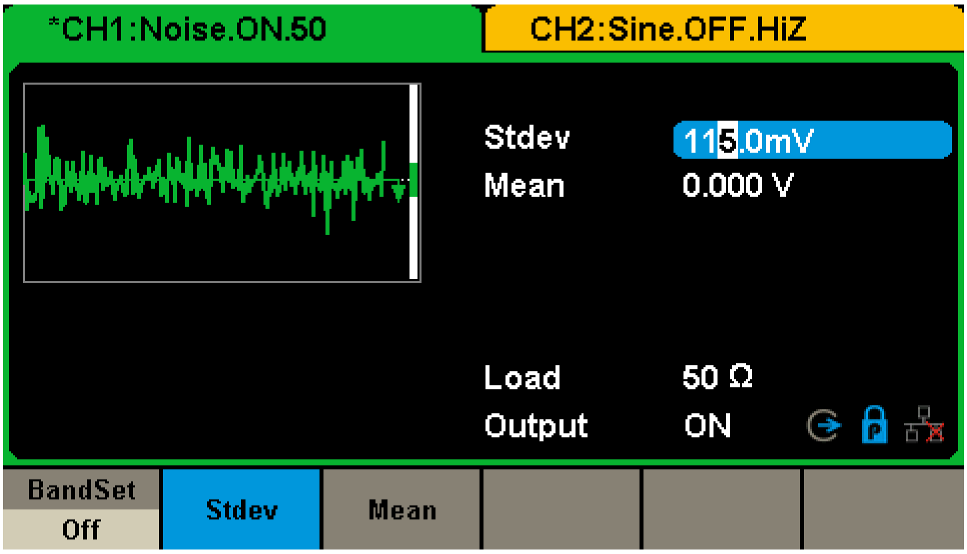


Figure 25 SDG2000X noise setting interface

The analog channel of the arbitrary waveform generator is a low-pass channel. Therefore, after the white Gaussian noise passes through the analog channel, it becomes band-limited white Gaussian noise, and its bandwidth is generally measured by the -3dB cut-off point.

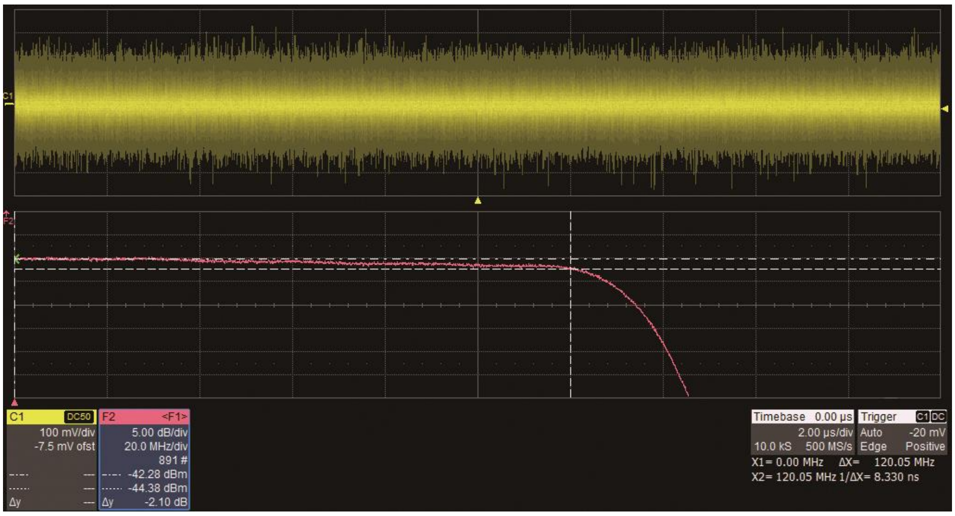


Figure 26: Using White Gaussian noise to test the frequency response of the analog channel of an SDG2000X

Since the spectrum of the White Gaussian noise itself is uniform, the frequency response of the band-limited White Gaussian noise generated by the low pass channel is actually the frequency response of the low pass channel. Using this feature, white Gaussian noise can be used to test the

frequency response of the analog channel of the arbitrary waveform generator.
The noise of SDGs series is generated by a special White Gaussian noise generator, and its repetition period is more than 100 years. It can be regarded as a random noise in most engineering applications.

6. Arbitrary waveform output

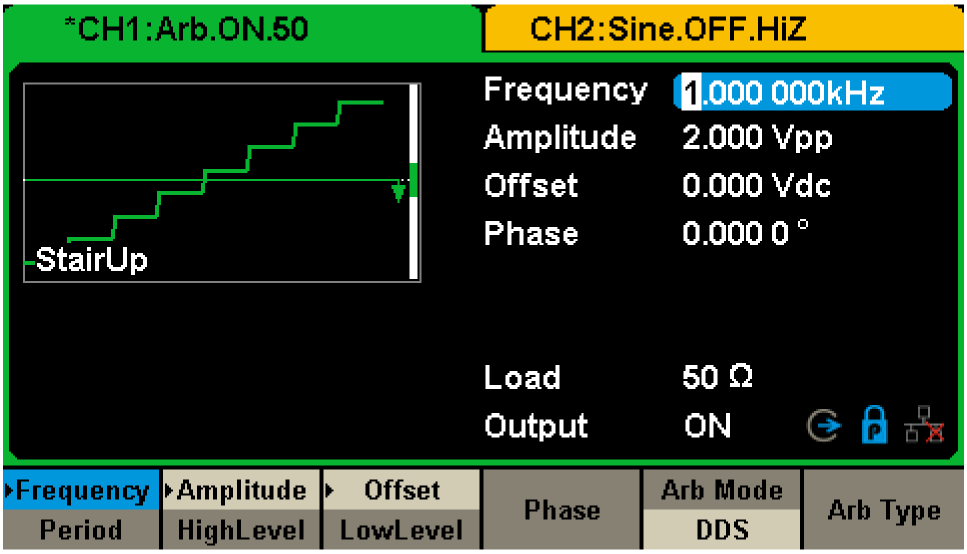


Figure 27 SDG2000X arbitrary waveform setting interface

In addition to the basic waveforms described above, the arbitrary waveform generator can also build many special waveforms in the "arbitrary waveform" mode. There are three ways to set it. We can load a waveform from the built-in functions included in the generator.
We can also programmatically generate waveform files through tools such as Matlab and import them into the generator. In addition, we can also draw waveforms not included in the built-in waveforms through arbitrary waveform drawing software. In the SDG2000X series function / arbitrary waveform generator, the maximum length of the arbitrary waveform can reach 8 Mpts, and the output frequency range is between 1 μHz and 20 MHz.

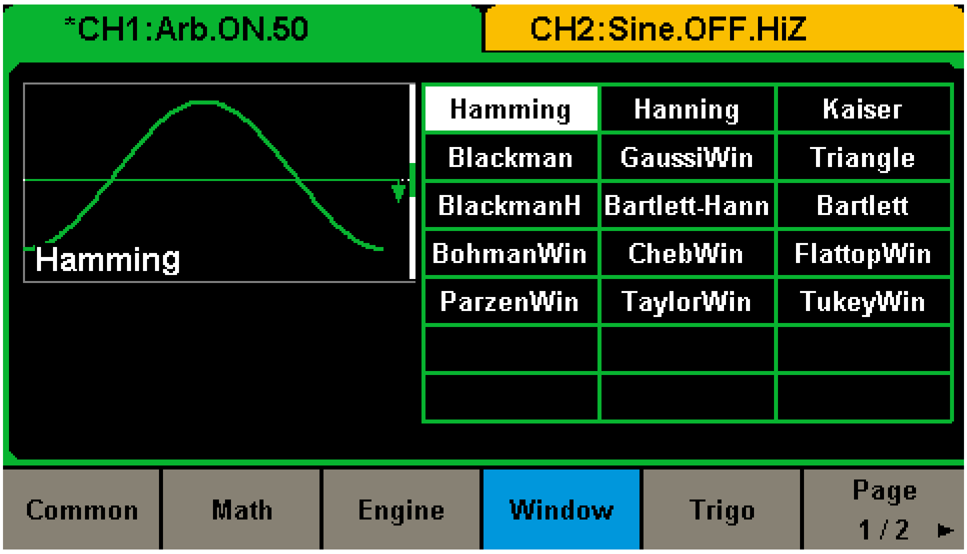


Figure 28 SDG2000X built-in waveforms

The selection interface of the built-in waveform is shown in Figure 28. The system classifies the built-in waveform according to 10 categories: Common, math, engine, window, trigonometry, square, medical, modulation, filter and demo. After loading the built-in waveform, the frequency, amplitude and offset can also be adjusted.

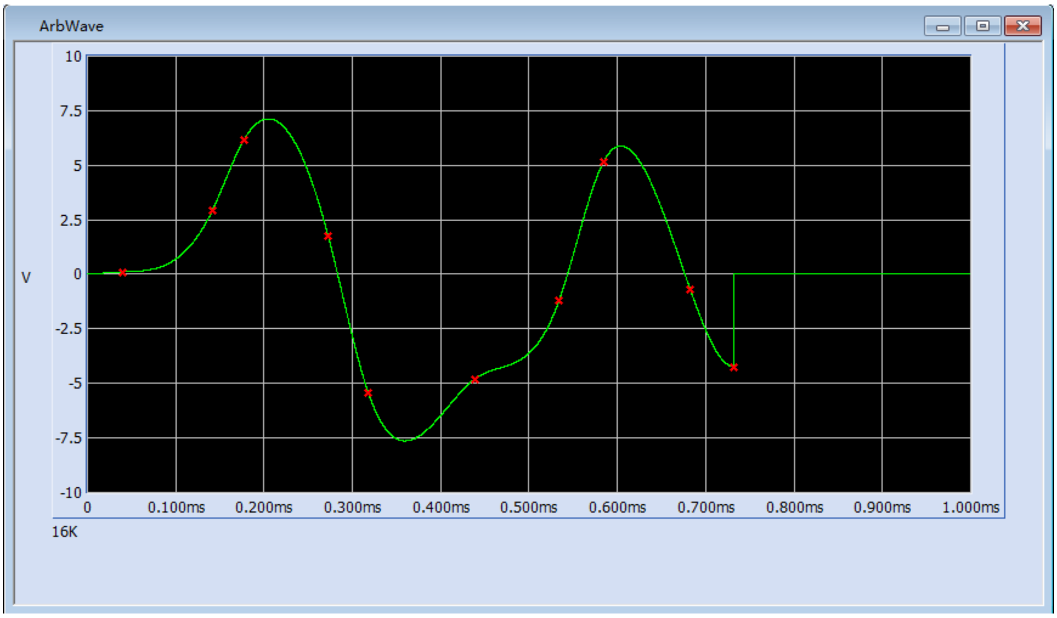


Figure 29: EasyWave arbitrary waveform drawing software

The entire series of arbitrary waveform generators produced by Siglent Technologies can use EasyWave arbitrary waveform drawing software. You can draw arbitrary waveforms by manual drawing, equation drawing, coordinate drawing, and more.

So far, we have introduced basic waveform output by the arbitrary waveform generator and its related parameters. Next, we will introduce analog modulation, sweep, burst and other waveform output.