Technical NOTE

GAMRY INSTRUMENTS

Waveform Generation and Frequency Resolution

Purpose of This Note

This Technical Note outlines how waveform signals are generated with a potentiostat. Further, the term “frequency resolution” is discussed which is often mentioned in specification sheets for potentiostats. But what exactly does this term describe and how meaningful is this parameter?

Introduction

When performing EIS experiments, a sine wave signal with varying frequencies (potentiostatic or galvanostatic) is applied to a cell. The general function of a sine wave has the form

$$E_t = E_0 \sin(\omega \cdot t) \qquad \text{Eq. 1}$$

with E_t as the applied signal at time t, amplitude E_0, and the radial frequency ω. The radial frequency can be also written as frequency f with $\omega = 2\pi \cdot f$.

Because a detailed description of EIS goes beyond the scope of this technical note, we mainly focus on how sine wave signals are generated.

> For more information on the theory of electrochemical impedance spectroscopy, see Gamry’s application note at www.gamry.com:
>
> **Basics of Electrochemical Impedance Spectroscopy**

Signal Digitalization and Limitations

In the past, waveform signals were generated with analog methods; older instruments used, for example, phase-locked loops (PLL) to create a sine wave. Now, signals are digitized. This means that a signal generator approximates the signal curve with a staircase form (see Figure 1). The width (time scale) and height (amplitude scale) of each single step depend on the sample rate and the magnitude resolution. The smaller these steps are the better a signal can be reproduced.

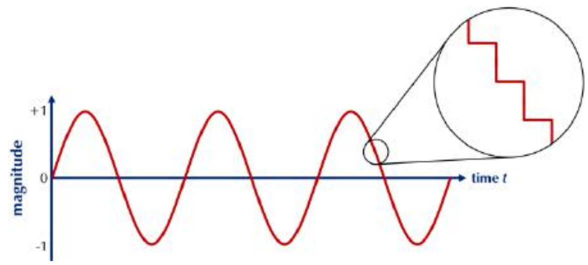

Figure 1. Graphical representation of a sine wave showing its digitized staircase form in greater detail.

High-frequency signals are generally the limiting factor in potentiostat instrumentation. The sample rate (also called “*clock rate*” or “*clock frequency*”) plays an important role. The clock frequency does not only define the step width of the generated signal but determines also the maximum achievable signal frequency. As a general rule, the clock frequency f_{CLK} must be at least twice as big as the signal frequency. The limiting frequency is also known as Nyquist frequency $f_{Nyquist}$ (see Eq. 2).

$$f_{Nyquist} = \frac{1}{2} f_{CLK} \qquad \text{Eq. 2}$$

Figure 2 illustrates this in more detail. The red curve resembles the target sine wave signal. The black dots show the clock frequency of the signal generator and the green curve the actual signal.

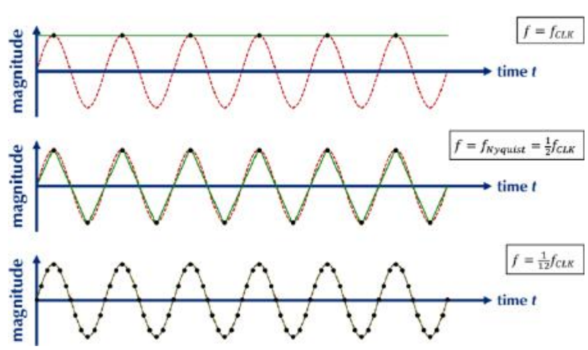

Figure 2. Influence of clock frequency on waveform generation.

You can see in Figure 2 that the sine wave cannot be reproduced if the signal frequency f is higher than $f_{Nyquist}$ (top). The generated signal is just a constant signal. A sine wave signal can be first reproduced if the signal frequency is equivalent to (middle) or lower than $f_{Nyquist}$ (bottom).

You can also notice that the sine wave is much better represented the larger f_{CLK} is compared to the signal frequency f, as more points can be used to create the signal. In the second case ($f = f_{Nyquist}$), the generated signal is only a triangle wave. Hence f_{CLK} is typically much higher than the maximum target frequency.

However, not only the clock frequency restricts the usable frequency range. High-frequency signals mean also fast signal changes (step height) which need to be processed by the control amplifier. In order to handle those signals, the bandwidth of the control amplifier (CA) needs to be sufficiently high so that signals can be properly adjusted and applied to a cell.

Other factors that determine the usable frequency range derive from the measurement setup. Cell cables can have a huge influence on the quality and bandwidth of a signal. Instrumental artifacts such as stray capacitance and inductive effects can drastically limit the frequency range.

For more information on instrument limitations, performance, and accuracy, see Gamry's application note at www.gamry.com:

Accuracy Contour Plots – Measurement and Discussion

In contrast to high frequencies, low-frequency signals can be controlled more easily because they resemble slow processes. Low frequencies do not have an instrumental but more a practical limitation. For example, a single sine wave of a 10 µHz signal lasts over 27 hours.

Waveform Generation

Gamry Instruments uses two different methods to generate a waveform depending on the frequency range. A direct digital synthesizer (DDS) sine wave generator is used to generate high-frequency signals. A digital-to-analog converter (DAC) is used for low-frequency signals. Figure 3 shows a very simplified diagram of a signal generator with both methods.

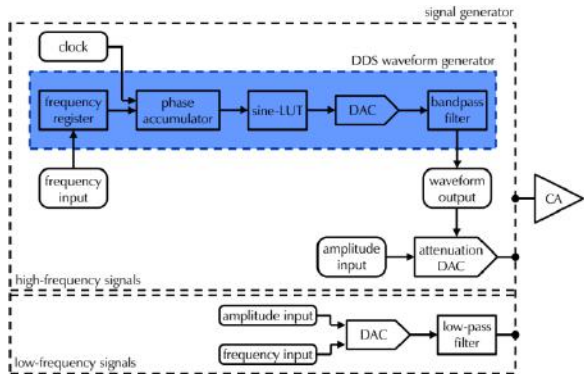

Figure 3. Simplified diagram of a signal generator showing both frequency-dependent methods to generate a sine wave. For details, see text.

The output signal of the signal generator is finally passed on to a control amplifier. It applies the signal to the cell and adjusts the signal accordingly by using the electrometer's input.

For a more detailed description of various instrumental terms and the functional principle of potentiostats, see Gamry's application note at www.gamry.com:

Understanding the Specifications of your Potentiostat

Following sections describe both methods that are used to generate waveform in more detail.

High-frequency signals

Each DDS waveform generator has a digital clock input (*clock*). Its reference clock frequency f_{CLK} determines the time resolution between individual signal points.

The frequency input is processed at the "*frequency register*" and read into the "*phase accumulator*". As the name implies, it uses not the magnitude of a sine wave but the phase information to generate a waveform. The reason is that the magnitude information of sine curves has a non-linear behavior, making it hard to generate. However, the phase shows a linear behavior (see Figure 4). Hence the phase curve can be easier generated and afterwards converted into a sine wave signal.

The phase accumulator generates a continuous digital phase signal which repeats itself each cycle. The step height $\Delta\theta$ of the phase is defined by the resolution of the phase accumulator. This means for example that the phase information is divided into 2^{32} bit-sections when using 32-bit resolution.

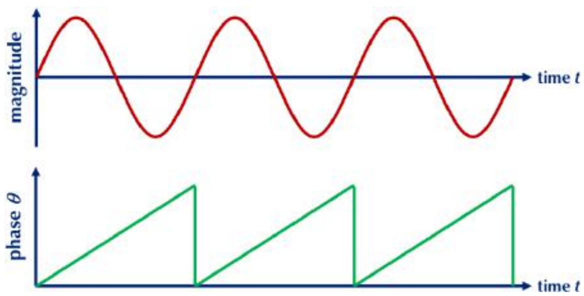

Figure 4. Magnitude and phase behavior of a sine wave. For details, see text.

The output frequency can be adjusted by controlling the number of phase-bits that are scanned. This parameter is also called “*frequency tuning word*” (FTW). Each applicable frequency value has a corresponding FTW-value which is stored in the “*frequency register*” (see Figure 3). After entering a frequency input value, the corresponding FTW-value is retrieved from the frequency register and subsequently read into the phase accumulator. The phase accumulator then creates a phase signal that corresponds to the input frequency. The general output equation of a DDS can be expressed as follows (in case of a 32-bit phase accumulator).

$$f_{out} = FTW \cdot \frac{\Delta\theta}{\Delta t} = \frac{FTW}{2^{32}} \cdot f_{CLK} \qquad \text{Eq. 3}$$

Δt is the step width of the digital signal, which is generally expressed as its reciprocal value f_{CLK}.

Note that the output frequency f_{out} would be equivalent to the clock frequency f_{CLK} of the DDS if the full phase range is scanned by the phase accumulator (FTW = 2^{32}). However, generating a sine wave signal with this frequency is not possible as discussed earlier and shown in Figure 2. Hence FTW-values only range from 0 to 2^{31}-1 (for a 32-bit phase accumulator) and cover the lower half of available phase-bits. This means only signals with a maximum frequency of $f_{Nyquist}$ can be generated.

The output signal of the phase accumulator contains phase information. It has to be converted into amplitude in order to create a sine wave. This is done in a so-called “*sine look-up table*” (sine-LUT). Each phase value in this table is assigned to an amplitude value. In a final step, converted amplitude values are processed in a digital-to-analog converter (DAC). It generates the sine wave with the requested frequency.

A “*bandpass filter*“ is used to filter out unwanted portions resulting in a smooth output signal. It removes the steps of the DDS output and prevents drifts in the signal. Following paragraphs illustrate this in more detail.

Figure 5 shows a 1 MHz sine wave output signal measured with an Interface 5000. The blue curve shows the output after the phase accumulator. Note that the clock frequency is 24 MHz. Hence a single sine wave exhibits 24 signal steps. The total signal is superimposed by high-frequency noise. In contrast, the filtered output signal (red curve) is smooth and the staircase form is nearly completely filtered out. Further, the signal’s noise is also drastically reduced. The final output signal resembles more an analog signal.

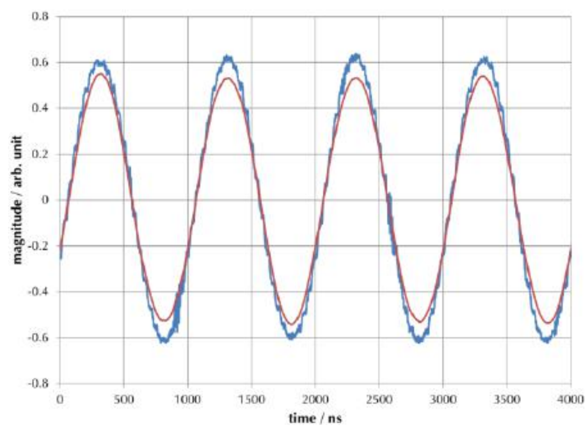

Figure 5. Sine wave output of an Interface 5000 before (blue) and after filtering (red).

Figure 6 compares the Fast-Fourier-Transformation (FFT) diagrams of both sine wave signals that are shown in Figure 5. The sine wave signals are displayed in the frequency-domain. Figure 6A shows the unfiltered signal and Figure 6B shows the filtered signal.

Both plots show a major signal peak at 1 MHz which resembles the sine wave’s base frequency. Additional peaks can be found at the harmonics of the sine wave’s base frequency which is in this case *n* times 1 MHz (*n* = 2, 3, 4, …). These peaks are nearly completely filtered out by the filter as shown in Figure 6B.

Not displayed in Figure 6 is the frequency range around the clock frequency (24 MHz). Usually, the FFT diagram would also show a larger peak at this frequency. However, this portion can be also filtered out and does not generally affect the quality of the applied signal.

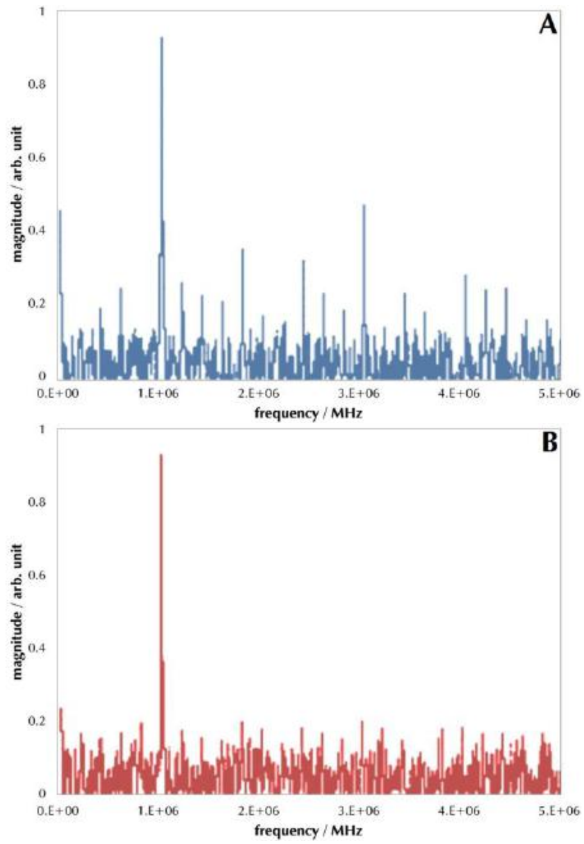

Figure 6. FFT of sine wave output signal shown in Figure 5. (A) unfiltered signal, (B) filtered signal. For details, see text.

In a final step, the filtered signal is read into an "*attenuation DAC*" which processes the input amplitude. The DDS output signal is always generated with maximum amplitude. The attenuation DAC adjusts the signal amplitude according to the requested amplitude. The output signal of the signal generated is then passed on to the control amplifier where it is applied to a cell.

The general output equation of a DDS (Equation 3) can be also used to calculate its minimum frequency (FTW = 1). For example, a 24 MHz DDS with a 32-bit phase accumulator can create a sine wave with a minimum frequency of about 5.6 mHz. This is also the frequency resolution of the DDS. All higher frequencies are integral multiples of this value.

Low-frequency signals

As discussed before, a DDS has a minimum frequency depending on its clock frequency and the resolution of the phase accumulator. Hence Gamry uses a DAC to generate waveform signals with lower frequencies (< 100 Hz), see Figure 3. Low-frequency waveforms are generally easier to control because signal changes are much smaller compared to high-frequency signals. The DAC processes both input frequency and amplitude and gradually scans the signal according to the input parameters. A "*low-pass filter*" smooths the output signal before it is processed at the control amplifier.

There is technically no lower frequency limit but there are practical limits. As mentioned earlier, sine waves in the µHz-range take several hours.

Summary

This technical note describes how waveforms are generated with a potentiostat. Gamry uses for high-frequency signals a direct digital synthesizer sine generator. However, the frequency range is limited by its resolution and sample rate. Hence a digital-to-analog converter which gradually scans the signal is used for lower frequencies.

Basically, low-frequency signals are not the limiting factor for potentiostat instrumentation. Limitations have more practical reasons because experiments can take very long. In contrast, various factors such as sample rate limit high-frequency signals. In addition, instrumental factors such as capacitive and inductive effects resulting from the cell cable and the setup can drastically affect the quality and bandwidth of a signal.

The term "frequency resolution" is often mentioned in spec sheets for potentiostats. However, it can be misleading and is generally not very informative. If anything, frequency resolution is only interesting for high-frequency signals.

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