SIGNAL RECOVERY

What is a Boxcar Averager?

Introduction

The *boxcar averager*, also known as a *boxcar integrator, boxcar detector,* or *gated integrator* is a sampling instrument that integrates the applied input signal during a predefined *gatewidth* or *aperture width,* starting at a predefined *trigger, gate,* or *aperture delay* after an applied trigger. Each of these integrated samples of input signal can then be averaged, using either an analog averager or by digitizing each sample and then averaging the resulting digital values.

The boxcar therefore performs signal recovery by three methods. First, the input signal only affects the output during the period in which it is being sampled; at all other times its level is unimportant, other than the need to avoid causing an input overload for which the recovery time might affect a subsequent sample. The sampling window achieves temporal separation of the signal from the noise, and it is often the biggest single contributor to improving signal to noise ratio. For example, in experiments using pulsed laser sources the signal being measured may only be a few nanoseconds wide, while the repetition rate is at most a few tens of hertz, yielding a signal duty factor of the order of 10^{-8}. In such cases the boxcar gives a convenient way of extracting the signal of interest.

Second, the signal is integrated during the gate width, unlike common sample and hold circuits that simply take a "snapshot" measurement of the signal level at one point in time. Hence if there is noise or other interference present at the input at frequencies that are much higher than the reciprocal of the gatewidth then these will be suppressed.

Finally, the measured samples are themselves averaged, ensuring that low frequency fluctuation or noise, which would cause sample-to-sample variation, is also diminished.

Operating Modes

The boxcar is normally used in one of two modes. In s*tatic gate* work, the time position of the sampling gatewidth relative to the applied trigger (i.e. the gate delay) is fixed, so that the instrument monitors the same point in time on the applied signal. This mode is commonly used to determine how a single feature (for example a peak) in a signal changes as a function of time, typically as some other experimental parameter is adjusted. For example, if the decay time of a fluorescent material were dependent on temperature, then this could be studied by using a pulsed laser to excite it and a photodetector to detect the resulting optical signal. The boxcar averager would be set to measure this photodetector's output signal at a fixed gate delay after the laser pulse, so that by changing the temperature of the material while recording the boxcar output the required information could be obtained.

In *waveform recovery* mode the boxcar operates rather like a sampling oscilloscope, with the gate delay being swept over a range of values while the output is recorded. The result is a record of the signal waveform.

In commercial boxcar instruments, the output was traditionally recorded using an analog chart recorder. The recorder's Y input was connected to the output from the boxcar's output averager, and its X input was driven either by a voltage proportional to the experimental parameter being studied (in static gate work) or by one proportional to the gate delay (in waveform recovery). Nowadays the boxcar's output is usually digitized for recording by a computer and the trigger delay is set using a separate digital delay generator. This makes it possible to use a computer to run the whole experiment and record the resulting data.

Boxcar averagers can recover very fast waveforms and resolve features down to sub nanosecond level. However they can be time inefficient if used for waveform recovery and in such applications signal averagers and storage oscilloscopes may offer better performance. They remain very useful for static gate work.

General Principles of Operation

The heart of any boxcar is the *gated integrator* circuit, shown in simplified form in Figure 1. This circuit is simply an RC low-pass filter gated by switch S_1, (the sampling gate). As shown, the gated integrator has unity DC signal gain.
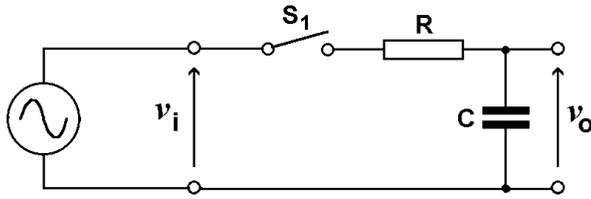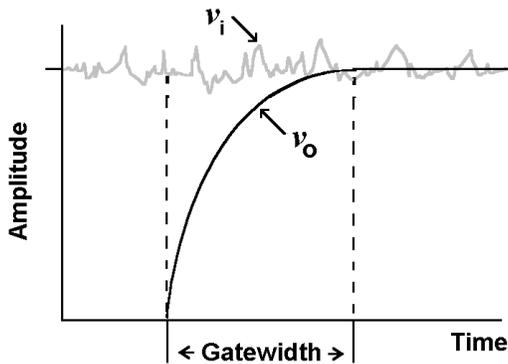

Figure 1, Gated Integrator

Figure 2, Gated Integrator Operation

When the gate opens (switch S_1 closes) the output voltage v_o starts to rise exponentially towards v_i, as shown in Figure 2, where the gatewidth is given as being small in relation to long term changes in v_i. The gate time constant (set by the product RC) is adjusted so that the v_o is typically within a few percent of the input v_i by the end of the selected gate width. Consequently high frequency components of the input

signal are removed. The equivalent noise bandwidth is simply $B_{no} = \dfrac{1}{4RC}$

The integral of the gate sample is the voltage v_o at the end of the gatewidth. This can either be integrated in an analog output averager or immediately digitized for averaging, after which the sampling circuit is reset ready for the next trigger.

The rest of the boxcar consists of the output averager, discussed later, and trigger processing and delay circuits. The **SIGNAL RECOVERY** model 4121B boxcar averager has a trigger input that is similar in design to those used on oscilloscopes, allowing triggering on a variety of waveforms. Following the trigger, a delay circuit allows the position in time start of the gate to be adjusted while a variable pulse generator creates the gate pulse.

The overall maximum trigger rate of the instrument is set by the gate delay, gate width, averager processing and reset times, with the model 4121B offering the fastest rate of commercially available units of up to 80 kHz; competitive instruments are limited to about 20 kHz.

Static Gate Boxcar Averaging

In the *static gate* boxcar averager the length of the trigger delay is fixed and the intention is usually to determine the amplitude of some 'spike' or narrow feature of a waveform that is typically much narrower than the repetition period set by the overall trigger rate.

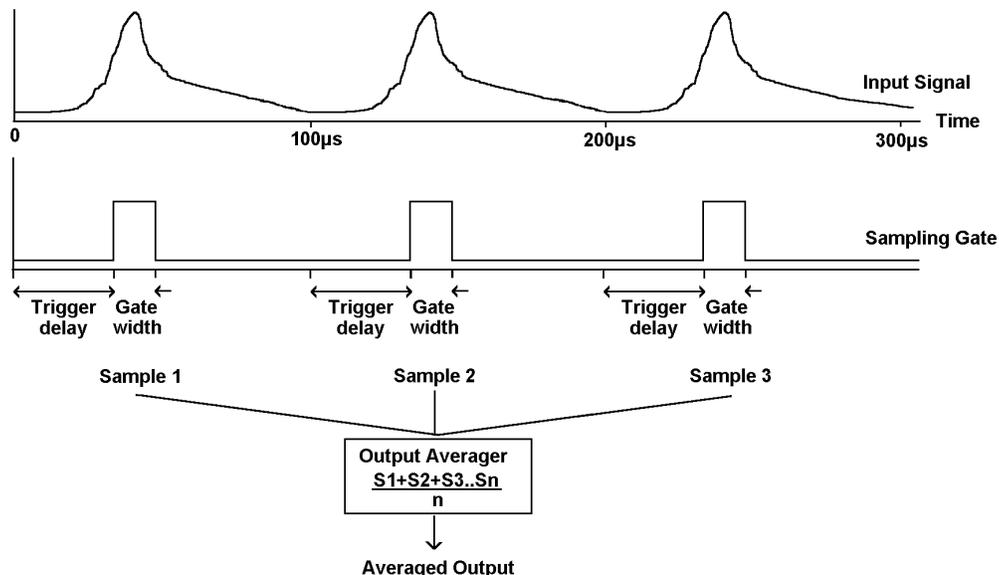Consider the situation shown in Figure 3 below.

Figure 3, Boxcar Averager Operation - Static Gate Mode

The input signal consists of a repetitive waveform triggered at a 10 kHz rate, so that each cycle lasts 100 μs. The trigger delay is set to open the gate just before the feature of interest and the gatewidth is set to "bracket" this feature. Each sample results in an integral representing the area under the signal curve for the duration of the gate, and these samples are then averaged in the output averager.

When using a linear output averager, all samples have equal weight and so the output will rise in a linear staircase fashion as shown in Figure 4, curve A.
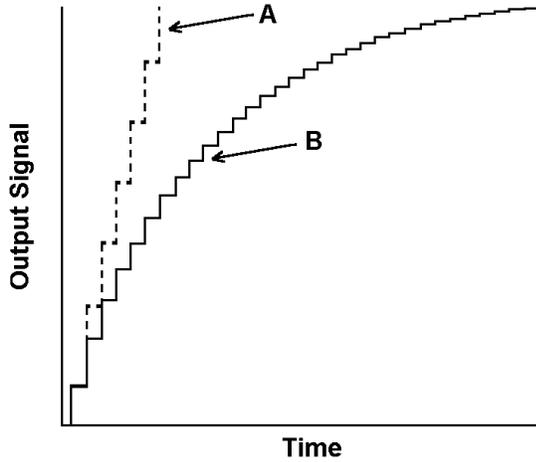
Figure 4, Gated Integrator Output Averager
A) linear B) exponential

Each step in this curve represent a new sample becoming available, which in turn corresponds to a trigger cycle. In this *linear averaging* mode, the desired number of signal samples (n) is selected; after n triggers have occurred, a switch or other method is used to reset the output averager. Since the signal component of the samples will add linearly, but random noise samples add vectorially, after n samples of a constant amplitude signal (S) plus white noise (N), and after maximizing the gate width to suit the signal waveshape, the output Signal to Noise ratio (SNR$_{Out}$) is given by:

$$\text{SNR}_{\text{Out}} = \frac{S_1 + S_2 + S_3 + \cdots + S_n}{\sqrt{\left(N_1{}^2 + N_2{}^2 + N_3{}^2 + \cdots + N_n{}^2\right)}}$$

$$\text{SNR}_{\text{Out}} == \frac{nS}{\sqrt{\left(nN^2\right)}} = \frac{S}{N}\sqrt{n} = \text{SNR}_{\text{in}}\sqrt{n}$$

so that the Signal to Noise Improvement Ratio (SNIR) is:

$$\text{SNIR} = \frac{\text{SNR}_{\text{out}}}{\text{SNR}_{\text{in}}}\left(= \frac{\text{SNR}\,(n\,\text{samples})}{\text{SNR}(1\ \text{sample})}\right) = \sqrt{n}$$

Note that in this operating mode, it is easiest to think in terms of time averaging since the equivalent noise bandwidth of the gated integrator circuit is not constant but will decrease with increasing n.

The linear averager suffers from the disadvantage of needing to be reset after each set of triggers. Although this is not difficult if the output averager is implemented digitally (for example by using a program running in an attached PC), it is not as easy when using analog techniques. Historically, analog versions were more common and so in such cases the output used *exponential averaging.* Essentially this consists of nothing more than a further gated integrator stage, but this time with a time constant much longer than the gate width. The gate on this stage is operated for a short fixed period (typically a few microseconds) to apply the sample voltages out of the input averager to the output averager, with one such gate per trigger cycle.

With exponential averaging, if the samples from the input averager are similar in amplitude then the output from the output averager will rise exponentially as shown in Figure 4, curve B. Again, each step corresponds to a new sample becoming available, and hence a trigger cycle.

Waveform Recovery Boxcar Averager

Boxcar averagers can also be used for *waveform recovery,* where the intention is to record the waveform of the input signal. In this mode of operation the trigger delay is not fixed but rather is incremented by a fixed amount on successive groups of n triggers so that it sweeps between *initial delay* and *final delay* values. In this mode, the boxcar output is a replica of the signal waveform and the boxcar can be regarded as a time-translation device that can slow down and recover fast waveforms.

Figure 5 (overleaf) gives a simplified view of this mode. The gate width is now set to be much shorter than the signal period. The first set of n samples is taken after a trigger delay set to the initial delay setting. This group of samples is then averaged by the output averager and appears as point A on the output plot. The boxcar counts the applied triggers and after the first set of n have been detected, the trigger delay is incremented and the cycle repeats, resulting in point B. The process continues (generating point C and further.

points) until the trigger delay is equal to the preset final delay value. The number of points *m* on the output waveform record is:

$$m = \frac{\text{Final Delay - Initial Delay}}{\text{Delay Increment}}$$

It will therefore be seen that as the delay increment is reduced the time resolution of the recorded waveform will improve, since there are more points. The downside is that the time to record the waveform will also increase.
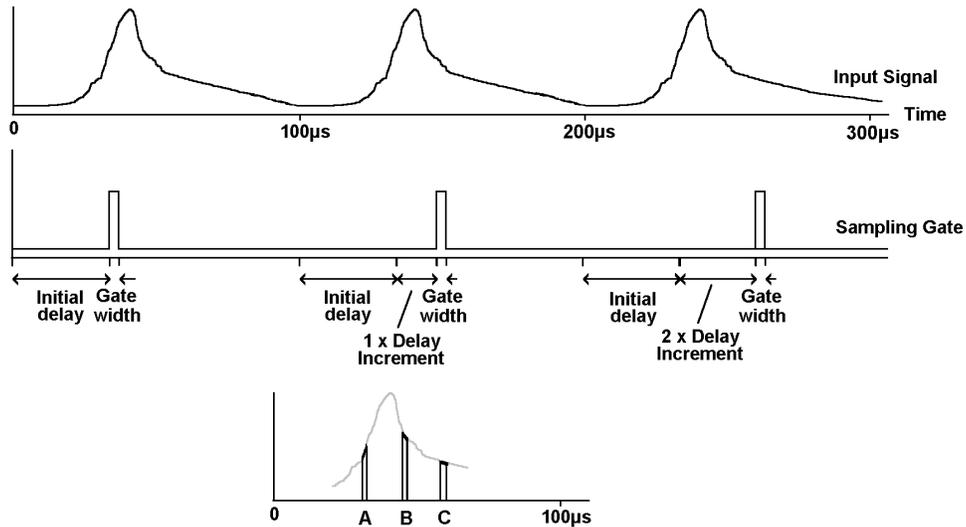
Figure 5, Boxcar Averager Operation - Waveform Recovery Mode

Further Information

This Technical Note is intended as an introduction to the concept of boxcar averaging. Additional information may be found in other **SIGNAL RECOVERY** publications, all of which may be downloaded from our website at **www.signalrecovery.com**

In addition staff at any of our offices or those of our distributors and representatives will be happy to answer any questions you may have. For contact details, please visit our website at **www.signalrecovery.com**

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