The Boxcar Detector

A synchronous detector which is used to recover waveforms buried in noise

by J. D. W. Abernethy, B.A.

The boxcar detector* is a signal recovery instrument which is used either to retrieve the waveform of a repetitive signal from noise or to measure the amplitude of a repetitive pulse buried in a noise. It has two modes of operations, 'scan' and 'single-point', the former being used for waveform retrieval and the latter for pulse measurement. Waveform retrieval applications include on-line impulse testing of electro-mechanical systems, measuring the decay time of phosphors, time-of-flight mass spectroscopy and the measurement of magnetic field penetration in superconductors. In the single-point mode the boxcar will measure noise-obscured pulses such as those found in applications concerned with pulsed radar, acoustic paramagnetic resonance, Q-switched lasers, non-linear optical effects etc. The boxcar can also be used to make accurate permanent records of waveforms, even when noise is not a problem, because of its ability to readout on X-Y plotters.

As an example of an impulse testing application, the boxcar may be used to determine the response of a loudspeaker and its surroundings without taking any precautions to screen the system from outside noise. In a typical experiment (see Fig. 1) a repetitive pulse is applied to the loudspeaker and the resulting signal, together with extraneous noise, is picked up by the microphone and fed into the boxcar. The boxcar is also supplied with a synchronous reference pulse. The output of the boxcar, an internally generated ramp and the modified microphone signal, is applied to an X-Y plotter which reproduces the input waveform with the noise reduced.

The boxcar is basically a sample-and-hold system the sampling time of which is determined by a reference pulse which is related to the signal of interest. In its single-point mode the boxcar so arranges the timing and width of the sampling 'window' that it coincides with the signal pulse. Thus only the pulse and the noise occurring during the same period of time contribute to the output. See Fig. 2(a). In the scan mode, see Fig. 2 (b), the operation is somewhat similar except that the sampling window, instead of having a fixed time relation to the signal of interest, is slowly swept across it, thus producing at the output a lengthened replica of the input waveform.

Waveform averaging

The boxcar plots out the waveform of a repetitive signal buried in noise by correlating successive parts of the input waveform with a reference pulse and averaging the result with a low-pass filter.

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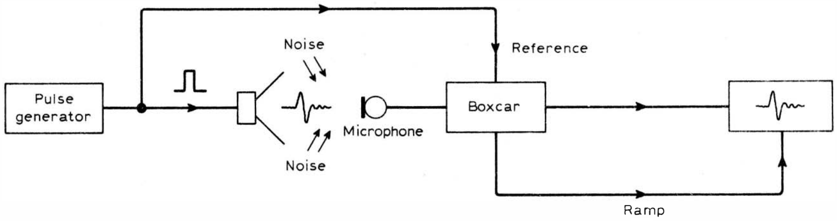
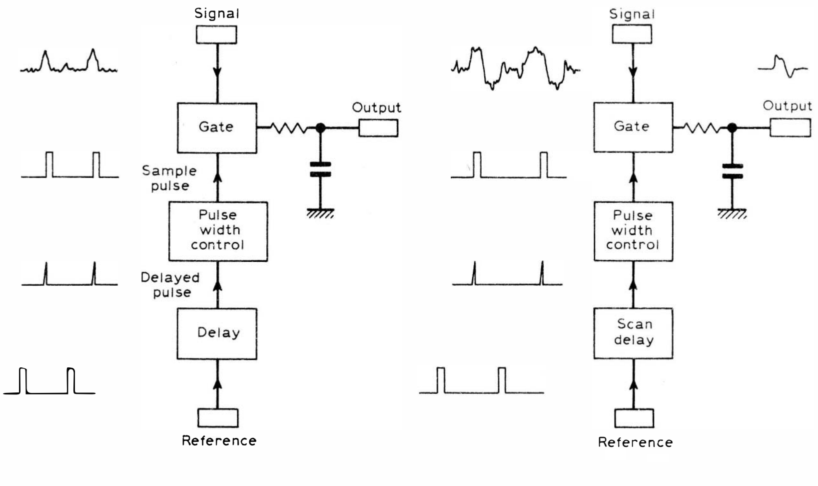


Fig. 1. A typical application. The measurement of acoustic response.



(a) (b)

Fig. 2. Block diagrams (a) single point operation (b) scan mode.

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*The origin of the word boxcar is somewhat obscure but it is thought to be derived from the similarity in outline of an American boxcar train and a train of pulses viewed on an oscilloscope.

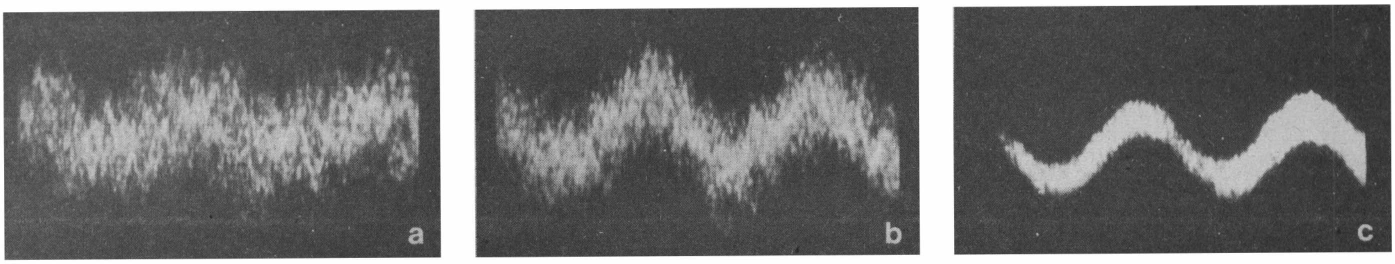


Fig. 3. A demonstration of correlation and averaging as a means of waveform recovery: (a) signal plus noise displayed on a short persistence oscilloscope using the internal timebase; (b) the same display with the timebase externally triggered by a reference waveform which is coherent with the signal; (c) this is the same as (b) with the c.r.t. replaced with one of long persistence.

As a simple example of waveform recovery by correlation and averaging, three oscilloscope traces of a repetitive signal and noise are shown in Fig. 3. In (a) the signal and noise are displayed on a short persistence oscilloscope with the timebase triggered internally. In addition to vertical errors caused by the noise there are also horizontal noise errors. In (b) the timebase is triggered externally by a reference which is coherent with the signal. It can be seen that this simple correlation process considerably improves the observed signal/noise ratio. In (c) the timebase is also triggered externally, but the tube persistence is increased. The improvement from (b) to (c) is due to the increase in the optical time constant.

The example is given to illustrate the principle of correlation and averaging as applied to waveform recovery, and it is not intended to be a serious solution to the problem. However, the principle, somewhat extended, leads to the idea of the multi-channel averager and from there to the functioning of a boxcar.

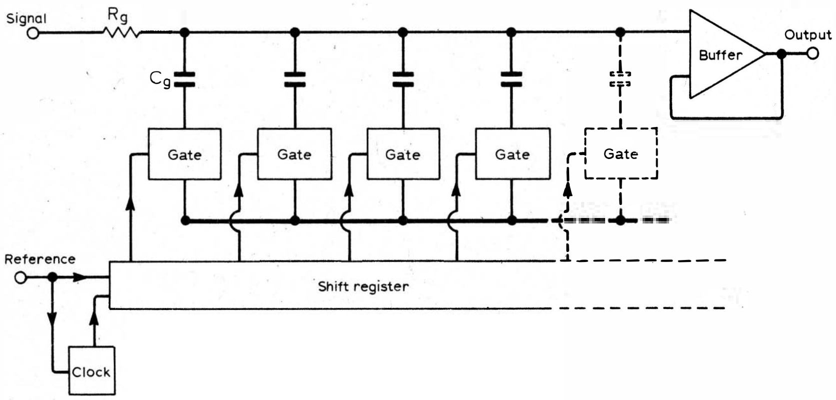
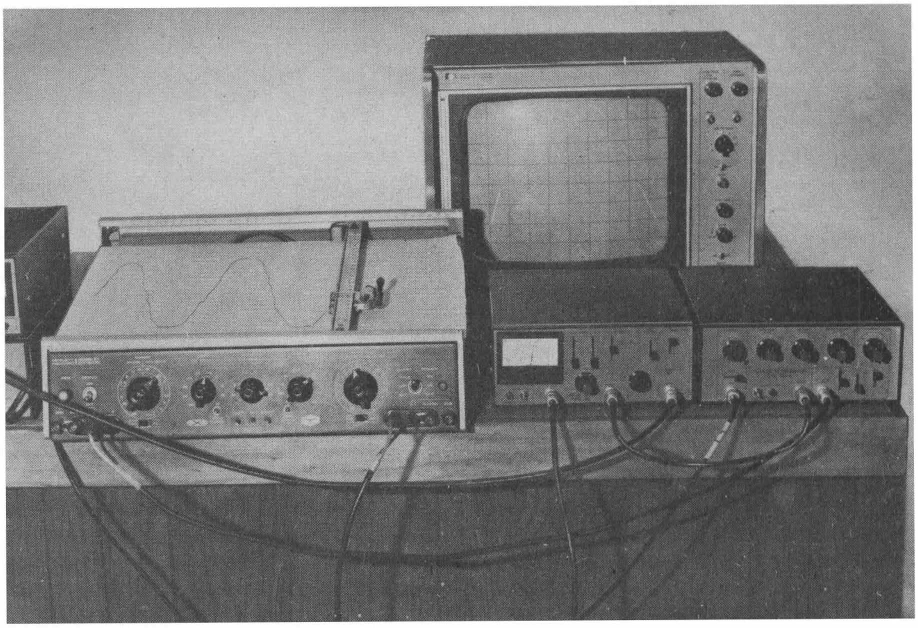


Fig. 4. Block diagram of multi-channel averager.



The boxcar detector in use.

Multi-channel averager

The multi-channel averager is another correlation instrument which is used specifically for recovering the waveform of a repetitive signal buried in noise. It operates by using a series of sampling gates (see Fig. 4) to divide each signal cycle into segments, the number depending on the resolution required. Storage capacitors connected to the gates charge, on each cycle, towards the mean voltages of the appropriate segments. The gates are triggered by a reference which is synchronous with the signal of interest and thus noise inputs which are not coherent with the reference are averaged towards zero. Because of its complexity (200 channels or more may be required to give sufficient resolution) the multi-channel averager is generally very expensive. A further consequence of its complexity is that the sampling gates need to be fairly simple and therefore are not always capable of the required sampling speed. The boxcar operated in the scan mode provides a much simpler and therefore less expensive instrument with fast-sampling capability.

Boxcar-scan mode

When the boxcar is operated in the scan mode its function is to sample and average each 'point' on the waveform in turn, moving to the next when the output has reached the voltage of the waveform at that point with sufficient accuracy. Scanning is achieved by changing the delay of the gate at a predetermined rate; called the scan rate. At the same time as the delay is scanned an output voltage is produced called the 'scan ramp output' which is proportional to the change in delay and provides a drive for the time axis of an X-Y plotter. A complete schematic diagram of the scan mode boxcar in operation is shown in Fig. 5. In practice the scan is continuous but, in order to make the illustration clearer, the scan is shown here as being in discrete steps, as if the delay and X-Y plotter were controlled by a staircase ramp.

It can be seen that the boxcar wastes information, that is to say it ignores most of the waveform, sampling only a small section per cycle. Therefore by comparison with a multi-channel averager operating with a resolution equivalent to n gates the boxcar will take n times as long to plot out a waveform with equal noise reduction. In normal practice this is a disadvantage only in low-speed experiments and in particular in medical experiments with low repetition rates: where an averager with 100 channels might take, for example, one minute to produce a result the boxcar

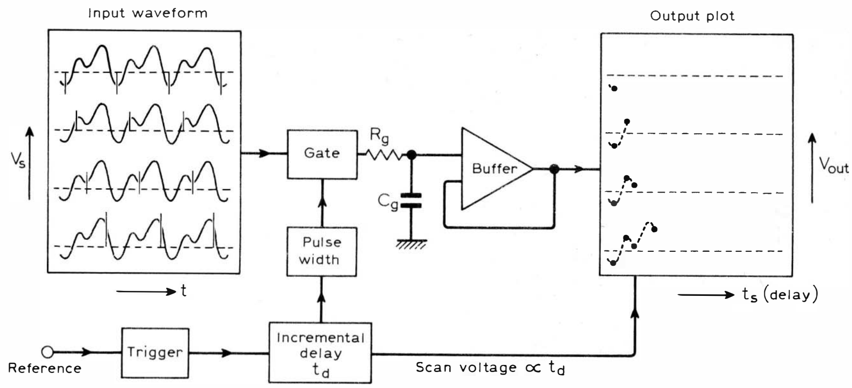


Fig. 5. (above) Point-to-point waveform averaging using the boxcar detector.

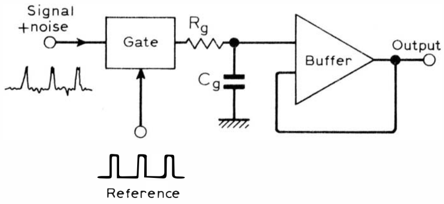
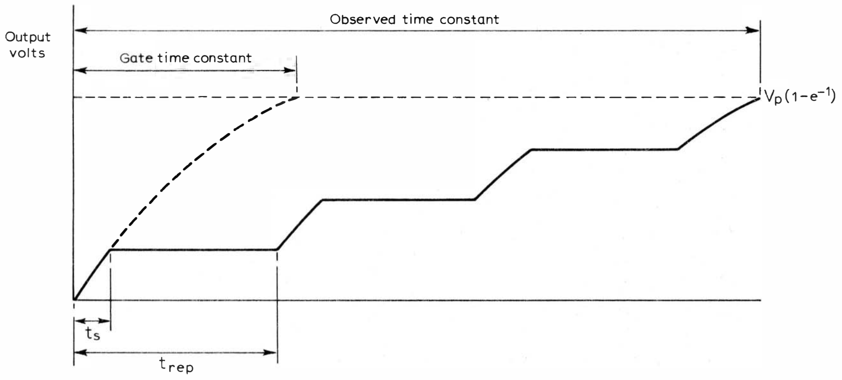


Fig. 6. (left) Sample and hold circuit.

Fig. 7. (below) The charging curve of C_g.



would take two hours. However in high-frequency experiments, for which the boxcar is ideally suited by virtue of its fast sampling capability, the result is usually plotted out in a matter of seconds.

Sample-and-hold system

The sampling section of the boxcar has to perform two functions: it must average the section of the waveform which occurs during the sampling period and it must hold the result until the next sample is taken. In order to do this the sample-and-hold configuration shown in Fig. 6 is used. When sampling, the gate is opened and the capacitor C_g charges towards the mean value of the sampled signal-plus-noise at a rate dependent on the product R_gC_g (called the 'gate time constant' t_g). Thus the time taken for the capacitor voltage to approach the signal voltage will be greater as t_g is increased; correspondingly, the voltage fluctuations on the capacitor due to noise inputs will be reduced and thus, although the measurement will take longer, the signal/noise ratio will be improved by increasing t_g.

Clearly the factor by which t_g is related to the overall response time is important since this establishes the terms of the trade-off between noise reduction and observation time. This relationship can be seen in Fig. 7 which shows the charging curve of C_g when a step-input (V_p) is applied and the reference consists of pulses giving a 'gate time' t_s occurring at intervals t_{rep}. It can be seen that during the time the gate is open the charging time constant is R_gC_g, whereas at the output there is a longer response time called the 'observed time constant', due to the fact that the charging circuitry is inactive for a large proportion of the time. The observed time constant (t_{obs}) is given by:

$$t_{obs}=t_g\times t_{rep}/t_s.$$

The noise averaging properties of the gate time constant are illustrated in Fig. 8 where oscilloscope traces show the voltage on C_g when a step function plus noise is applied to the signal input for (a) $t_g << t_s$ and (b) $t_g > t_s$. As one would expect the noise in (b) is reduced by the longer gate time constant. It might be thought, however, that equal noise reduction might be obtained by taking the output of (a) and smoothing it with a filter of time constant equal to the observed time constant of (b). The result of this is shown in (c) and it can be seen by comparison with (b) to be a less efficient noise averaging system. It should be pointed out that with certain types of noise spectra no significant difference between systems (b) and (c) can be detected, though it is obvious that from considerations of general purpose use (b) is to be preferred.

Operation in the can mode

On first acquaintance a boxcar can seem to be difficult to use because of its apparent complexity especially when used in the scan mode whereas, in fact, its operation is remarkably simple. An artificial experiment set up in the laboratory demonstrates this.

A waveform (see Fig. 9) buried in noise has a known repetition period of 10μs and is suspected of having components as short as 200ns. The boxcar of Fig. 10 is set up as follows:

t_i, initial delay, 0s: allows the sampling to start at the beginning of the waveform.

t_b, timebase, 10μs: gives a full scan across one cycle of the waveform.

t_s, sample width, 100ns: in order to resolve 200ns the next lowest time available is used.

t_c, output time constant, 0.3s: this is set

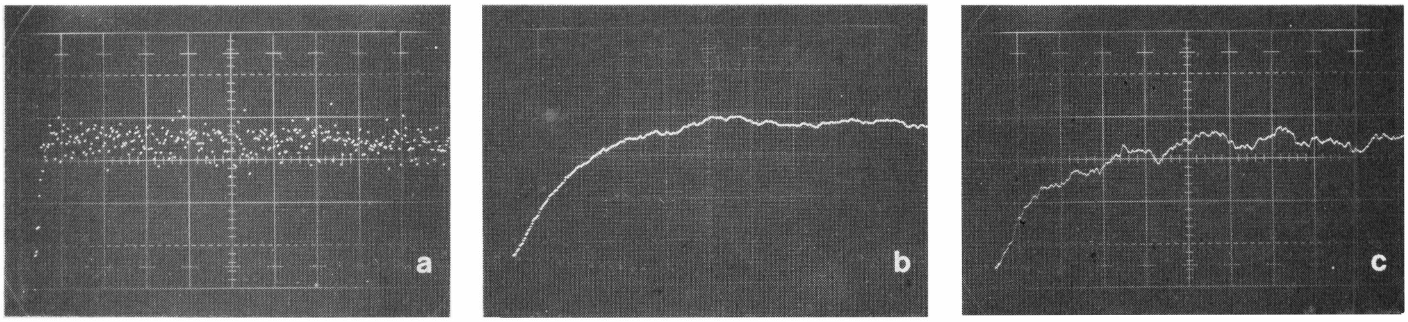
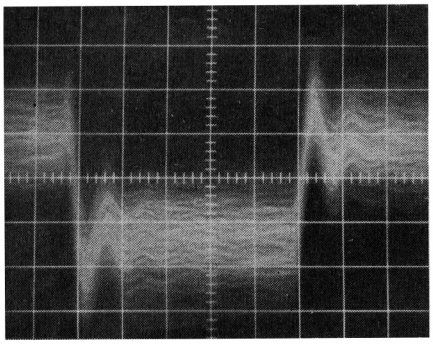
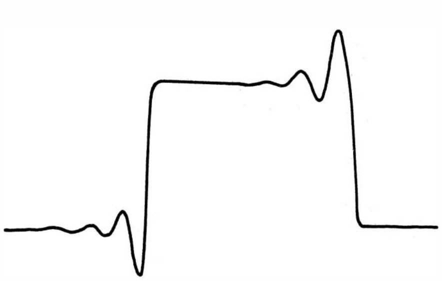


Fig. 8. (a) Voltage on C_g for $R_gC_g \ll t_s$, $t_{obs}=10\mu s$ (b) voltage on C_g for $R_gC_g > t_s$; $t_{obs}=10ms$ (c) voltage on C_g for $R_gC_g \ll t_s$ but smoothed by 10ms filter.





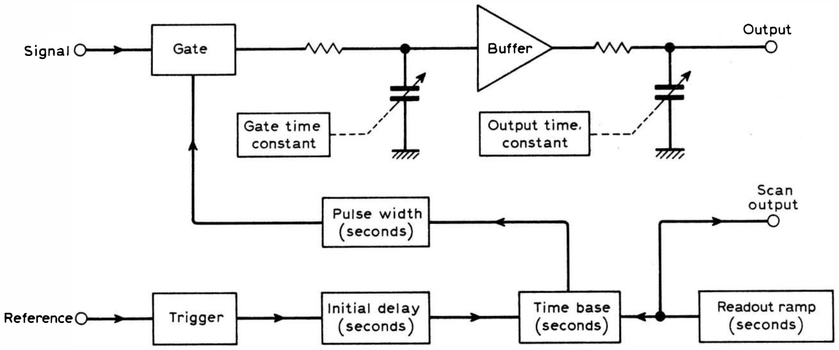


Fig. 9. (top left) a waveform buried in noise. Fig. 10 (lower drawing) Boxcar set-up for scan operation. Fig. 11. (top right) Resulting plot when the waveform of Fig. 9 is applied to the boxcar of Fig. 10.

empirically and in this case gives the required noise fluctuation of 1% of the waveform height.

t_g, gate time constant, 1ms: this is sufficiently long to provide efficient noise averaging within the gate while allowing the overall response time to be set by t_c.

t_r, scan readout time, 100s: the scan readout time needs to be sufficiently long to allow for the response time of the averaging system. It must be greater than $t_c \times t_b/t_s$.

The resulting plot is shown in Fig. 11.

Single-point mode

The boxcar, in its single-point mode in which it measures the mean amplitude of repetitive pulses buried in noise, bears a close resemblance to the phase-sensitive detector which is used to recover the mean amplitude of a simple periodic signal from noise. Both techniques employ a gate (or gates) followed by a low-pass filter and both are used in experiments where the signal is stimulated by a repetitive input which is also used to act as the reference. See Fig. 12. However, whereas the phase-sensitive detector is always gated at half-cycle intervals, the boxcar is gated so that it samples only the signal pulse plus any noise occurring during the sampling time. Since the pulse width may be less than 1% of the repetition period the sample-and-hold configuration shown in Fig. 6 is necessary to carry the information over from one cycle to the next. It can be seen that for pulse measurement, the boxcar is operated with fixed delay so that the sampling window 'encloses' the signal pulse and also with a gate time constant somewhat longer than the gate width so that the output is proportional to the mean amplitude of the pulse.

In Fig. 13 are shown the essential parts of a boxcar used in the single-point mode. The trigger input senses the reference voltage and fires a delay circuit which is manually adjustable so that the gate can be opened just before the signal pulse. This is followed by a pulse width control circuit which is set to close the gate just after the signal pulse.

Conclusion

The existence of high performance boxcar detectors now enables many new measurements to be made on systems, some yielding entirely new information, some eliminating lengthy experimental procedures. The ability to recover short pulses from noise has led to investigations of non-linear effects in systems where there is a limit on mean power dissipation but not on peak power. In addition, the ability to recover noise-obscured waveforms has resulted in the increasing use of impulse testing to characterize the response of systems, where previously the response was measured by swept frequency techniques. Although this article has not mentioned the subject of design criteria it should be added that the use of sampling circuits designed for other purposes will almost certainly give inferior results. In particular oscilloscope samplers are quite unsuitable partly because they have a fixed gate width which does not allow optimum signal recovery conditions to be attained and also because their design, quite reasonably, is aimed at speed of sampling rather than zero stability or linearity. As with any signal recovery system the dynamic range of the signal handling circuits is a most important parameter and worthwhile results will be obtained only if the gate and associated circuits are designed with signal recovery in mind.

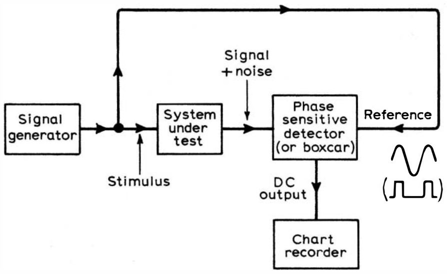


Fig. 12. The recovery of a repetitive signal from noise.

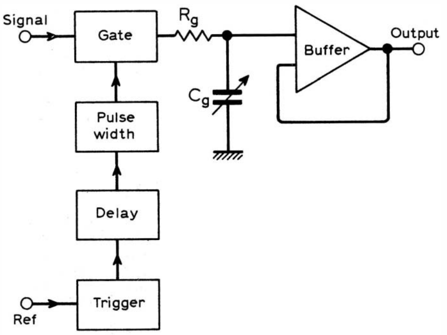


Fig. 13. Boxcar circuit in the single-point mode.