A versatile waveform generator for testing neuroelectric signal processors

André F. Kohn

Department of Electrical Engineering, Escola Politécnica da Universidade de São Paulo, São Paulo (Brazil)

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A multi-channel waveform generator was designed for testing neuroelectric signal processors. Smooth transient signals that resemble action potentials or evoked potentials are generated by a second order switched capacitor filter excited by brief rectangular pulses. The choice of an integrated circuit switched capacitor filter simplified the design by circumventing some of the disadvantages of conventional active filters. The waveform generator is versatile, with several signal parameters being independently adjustable from front panel controls: duration, waveshape, latency, amplitude and signal-to-noise ratio. The generator has been used for testing evoked potential acquisition and processing systems, for evaluating the effects of analog filters on evoked potentials and for testing systems designed to detect and classify trains of multi-unit action potentials.

Introduction

The processing of evoked potentials, nerve action potentials and motor unit action potentials may involve, among other things, analog and digital filtering, detection, synchronous averaging, artifact elimination, peak and latency determination, spectral analysis, pattern classification (e.g. Boston and Moller, 1985; Edin et al., 1988; Green et al., 1986; Mambrrito and De Luca, 1984; McGillem et al., 1981; Schmidt, 1984; Vibert and Costa, 1979). Many systems have been developed for the acquisition and processing of such neuroelectric signals (e.g. Miskiel and Ozdamar, 1987; Quint et al., 1985; Smith and Wheeler, 1988; van den Akker et al., 1983; not to mention medical equipment manufacturers). Specially tailored input signals are needed to efficiently carry out the testing and calibration of those complex multi-channel systems. An example is the case of evoked potentials where one has to test the preprocessing stage (e.g. analog filters), the acquisition stage (e.g. timing hardware), the processing stage (e.g. software for artifact detection, synchronous averaging, digital filtering, peak detection, latency estimation) and the display-operator interaction software (e.g. signal scanning, scale changes, cursor positioning). Conventional signal generators are not adequate testing devices because they do not generate the needed smooth transient multi-channel signals with independent controls for latencies, durations and waveshapes. A few specially designed waveform generators have been described in the literature and they can be divided in two classes. One class does not generate smooth waveforms, cannot be externally synchronized and presents great difficulties in adjusting duration and inter-peak latency while keeping the shape constant and vice versa (Blazek et al., 1975; Caballero et al., 1978).
The circuits proposed in these papers consist of a number of monostable circuits connected in tandem, with the last one activating the first, and therefore forming an oscillatory loop. The output waveform is obtained by integrating a weighed sum of each monostable's output. The other class generates smooth waveforms stored in EPROM memories and hence they are characterized by fixed duration and fixed waveform signals (Bach et al., 1984; Kaplan and Ondamar, 1987). They give a faithful copy of one type of signal (e.g. a visual evoked response) and any change in waveform and/or duration requires another EPROM. However, in most practical cases the exact reproduction of specific waveforms (e.g. real-life visual evoked responses or motor unit action potentials) is not needed. What is usually required is the generation of smooth transient waveforms which approximate biological signals and with capabilities for easy adjustment of shape, duration and latency, so as to accommodate several different applications.

This paper describes an electronic device that generates multi-channel transient signals with front panel provision for latency, waveform, duration and amplitude adjustments. The instrument is based on a switched capacitor filter complemented by digital and analog integrated circuits. It has been widely used in our laboratory for testing hardware and software being developed for the acquisition and processing of evoked potentials, motor unit action potentials and nerve action potentials.

Materials and Methods

Theoretical considerations

The main objective is to obtain a smooth "band-limited" transient signal with adjustable duration, waveform and latency. A simple method to generate such a signal is to apply a brief pulse to the input of a second-order low-pass filter. As is well known, the impulse response of such a filter is

\[ h(t) = \frac{(A_0 \sigma)}{(1 - \sigma^2)} \exp(-\frac{t}{\tau_0}) \sin\left(\frac{t}{\tau_0} / (1 - \sigma^2)\right) \]

\( t \geq 0 \quad \text{and} \quad 0 < \sigma < 1 \)

where \( A \) is the input impulse area, \( \omega_0 \) is the endamped natural angular frequency of the filter and \( \tau_0 \) is the damping ratio. The duration of each phase or half cycle is adjustable by changing \( \omega_0 \) while the waveform is determined by parameter \( \sigma \). For \( \sigma = 1 \) the impulse response is monophasic. As the value of \( \sigma \) is decreased, more phases or peaks appear in \( h(t) \). The latency may be varied by using a monostable to generate the input pulse. The desired ranges for \( \omega_0 \) and \( \sigma \) are 38-390 rad/s and 0.1-0.5, respectively. The former was computed from the range specified for the duration of each phase of the impulse response (about 0.8-6.5 ms) while the latter was chosen subjectively by looking at the resulting waveforms.

Conventional active filter implementations (i.e., using operational amplifiers) do not allow for the independent adjustment of both \( \omega_0 \) and \( \tau_0 \). Another difficulty with an active filter realization is the fact that the output amplitude is very sensitive on the value of \( \omega_0 \). Actually, the peak amplitude is proportional to \( \omega_0 \). For the desired \( \omega_0 \) range the amplitude will vary about 82-fold. This means that any change in waveform duration will have to be followed by a readjustment in amplitude, which is undesired from a practical point of view.

The choice of a switched capacitor filter implementation avoids these difficulties associated with conventional active filters. In this type of filter realization, \( \omega_0 \) is adjusted by changing a clock frequency (keeping \( \tau_0 \) unchanged) while \( \tau_0 \) may be varied by changing a resistance value (i.e., by using a potentiometer), without changing the value of \( \omega_0 \). The problem of high sensitivity of the output signal amplitude on \( \omega_0 \) is easily circumvented by designing a digital circuit that makes the input pulse area directly proportional to the clock period used for the switched capacitor filter. As \( \omega_0 \) is directly proportional to the clock frequency (a property of the switched capacitor filter), it follows that the output signal amplitude is independent of \( \omega_0 \). The output amplitude dependence on the waveform parameter \( \tau_0 \) is small, requiring only minor adjustments for \( \tau_0 \) near its maximum value (0.5).

Hardware implementation

A circuit diagram of a single channel of the waveform generator is presented in Fig. 1. The
It is probably better to use a trimpot (e.g., 100k) for offset adjustment.
components that are shared by all the channels are IC1, IC11, IC12, IC13, IC14, IC15 and IC16. The
heart of the generator is composed of two parts: (i) integrated circuits IC3, IC4, IC5, IC7, IC9 which are responsible for the automatic adjust-
ment of the input pulse area applied to the filter; (ii) integrated circuit IC6 which is a switched
 capacitor filter (MF10A from National Semiconductor) chosen to operate in mode 3 (Lucanetti,
1985). The clock frequency \( f_{SW} \) for switching the MF10A is generated by IC5. The proportion
\( \omega_{IN}/\omega_{SW} \) should be chosen as small as possible so that the switching frequency is much higher than the
signal's bandwidth. In this project this proportion
was chosen (using external resistors) 1/300.
Much smaller ratios result in large DC offsets at the
output and should be avoided. A short de-
scription of the whole circuit is given in what
follows.
The integrated circuit number 1 (IC1) is an
astable (555) that generates the internal stimulus
synchronization for all the channels. The desired
stimulus rate is adjusted by potentiometer P1.
Switch 1 (SW1) selects internal or external syn-
chronism (positions 1 or 2, respectively). The
delay from a stimulus trigger is adjustable by poten-
iometer P2 that sets the time constant for mono-
stable IC2. It is necessary to switch capacitors
(using switch SW2) to cover the desired latency
range. After the desired delay time elapses, the
output of the type D flip-flop (pin 5 of IC5) goes
to logic level 1. This makes the 'and' gate (IC7)
connect the clock signal generated by the second
astable (IC5) to the input of a counter (IC4).
When the final count \( N = 64 \) is reached, IC4's
output at pin 4 goes high, thereby clearing the
counter itself as well as flip-flop IC3. This disables
the clock connection from IC5 to the counter.
Only when a new stimulus pulse comes does the
state of the circuit change again. In this manner
IC3 generates a pulse whose average width is
\( (N - 0.5)T_{SW} \) (\( T_{SW} = 2\pi/\omega_{SW} \)). This pulse is ap-
plied to the input of the switched capacitor filter
(IC6) whose switching rate \( f_{SW} \) comes from asta-
able IC5. As \( \omega_{IN}/\omega_{SW} = 300 \), the product of the
input pulse width (proportional to area as ampli-
tude is constant) with \( \omega_{IN} \) is a constant equal to
\( 2\pi(N - 0.5)/300 \). Hence, larger \( \omega_{IN} \) (selected by
varying potentiometer P3 of IC3) will result in a correspondingly smaller input pulse area, and vice versa, making the output pulse amplitude con-
stant. The output pulse width from IC3 is not exactly \( (N - 0.5)T_{SW} \) due to the asymmetry be-
tween the timing of the delayed stimulus (output of
IC2) and the clock from astable IC1. The pulse width value will lie in the range \( (N - 1)T_{SW} \)
and \( NT_{SW} \) and hence the peak-to-peak time jitter re-
ferred to the average pulse width is \( 1/N \). The value chosen for \( N \) was 64 and therefore the
pulse width jitter is 0.15% of the average, which
causes no noticeable amplitude variability at the
filter's output.
Amplifier IC8 (1/4 074) permits gain adjust-
ment by means of potentiometer P6 as well as the
addition of noise with a level adjustable by poten-
iometer P5. Switch SW3 is in position 1 selects a
noiseless waveform while in position 2 a noisy
one. The noise source was built with four opera-
tional amplifiers connected in series (IC13–16).
In the waveform generator that we built we used
the same noise generator for all the channels. If
for some special application the inter channel
noise signals have to be uncorrelated then each
channel should have a separate noise generator
(two 741 Op. Amps. per channel). Switch SW4
selects the waveform polarity. Output 2 \( \overline{P} \) provides
the sum of all channels' waveforms. If lower out-
put signal levels are desired then one may increase
the value of R1 and/or decrease the value of R2
and P6). A lower signal level will be needed if the
generator is applied to amplifier inputs instead of
directly to A/D converter inputs or filters inputs.
The circuit requires only a ±5 V power supply
(for simplicity we used 7805 and 7905 regulators).
The switched capacitor filter (IC6) and all the
operational amplifiers use ±5 V. All the other ICs
use ±5 V. Standard cases were followed regarding
capacitor decoupling at the integrated circuits'
supply pins and physical separation of the digital
ICs from the analog in the printed circuit layout.
The load impedances (i.e. input impedances of the
systems under test) applied to the waveform gen-
erator outputs should be larger than 470 \( \Omega \). The
generator's external trigger input should be at
TTL levels.
The key features and specifications of the
waveform generator are listed in what follows: (1) simplicity of circuitry; (2) portability; (3) simplicity of operation (parameter adjustment by means of potentiometers); (4) expandability to any number of independent channels; (5) internal or external synchronism; (6) generation of smooth multiphase transient signals with adjustable durations and envelope decay; (7) possibility of adding adjustable levels of noise; (8) internal stimulus synchronism rates adjustable from about 0.3/s up to 40/s; (9) signal latencies (delays) from the stimulus synchronism adjustable from 0 up to 320 ms; (10) duration of each phase of the generated signal adjustable from about 0.8 up to 65 ms. The first three features mean that the instrument was designed to be inexpensive, easy to assemble and to use, and that it could be carried anywhere.

The specifications given above should satisfy many application needs but an examination of the circuitry shows that it is very easy to change or extend the specified ranges.

Results

Fig. 2 shows several output signals from the waveform generator. Fig. 2A shows seven waveforms having the same shape and amplitude but different durations. They were obtained by adjusting potentiometers P1 to seven different values covering the full range of u. All other potentiometers (including P4 which controls output amplitude) were left unchanged for all seven waveforms.

The oscilloscope gain and time-base were the same for all traces. The four channels of signals shown in Fig. 2B have different waveforms, latencies, durations, amplitudes and signal-to-noise ratio.

Fig. 3 shows the output signals from 5 different 4th order Butterworth bandpass filters that were excited by the same multiphasic input. Each input phase lasted about 0.8 ms and hence summed approximately the fast peaks in a brainstem auditory evoked response. The filters' high frequency cutoffs were held at 5 kHz while the low frequency cutoff frequencies were, from bottom to top, 3 Hz, 30 Hz, 100 Hz, 200 Hz and 300 Hz, respectively. Therefore, increases in the low-frequency cutoff caused decreases in latencies, sharp decreases in the first positive peak (P1) amplitude, decreases in the first peak-to-peak amplitude (P1, N1), increases in the next peak-to-peak amplitude (P1, P2), and so on.

The summed output Σ is useful if more complex waveforms are desired, as illustrated in Fig. 4. Fig. 4A could be viewed as a first approximation to an auditory evoked potential (the genera-
tials are wide apart. In the second (Fig. 4C), the 4th action peak starts right after the 3rd but they are still quite distinguishable. In Fig. 4D there is a large degree of overlap between the 3rd and 4th action potentials making them quite difficult to discriminate.

**Discussion**

Smooth transient signals, mimicking in essence evoked potentials or nerve and muscle action potentials, are extremely useful for testing neuroelectric signal acquisition and processing hardware and software, as well as for evaluating the effects of analog and digital filtering. The possibility of adding noise to the signals is helpful when testing systems running coherent averaging or detection/classification algorithms. The waveform generator, based on a switched capacitor filter, combines simplicity of use and assembly with versatility. The wide range of durations, latencies and wave-shapes covered by the generator and exemplified in Figs. 2–4 is needed for applications ranging from muscle and nerve action potentials to evoked potentials of different origins and modalities.

One of the critical issues in evoked potential studies is the distortion caused by the pre-processing analog filters on the transient neutral responses (Boston and Ainslie, 1980; Boston and Molle, 1985; Janssen et al., 1986). Interestingly enough, the results obtained in Fig. 3 are quite similar to many of those described in the literature for real life evoked potentials (see the 3 references above) hence suggesting that the signals synthesized by the waveform generator may be useful for providing first estimates of the effects of filtering (analog or digital) on evoked or spontaneous neural potentials. More complex signals (e.g., Fig. 4A), available from the summed output (Σ), would also be useful for testing filters, as well as, for example, for testing algorithms for automatic peak detection and latency measurement (Fridman et al., 1982). The signals of Fig. 4B–D would be very useful for testing detection/classification hardware and software for nerve and muscle action potentials (e.g. Eden et al., 1988; Mambrile and De Luca, 1984; Schmidt, 1984; Smith and Wheeler,
A difficult task found in such systems is the classification of overlapped discharges as exemplified in Fig. 4D. Controlled amounts of noise level could be added to the waveforms of Fig. 4 to mimic different experimental conditions.

The above described waveform generator should be useful to (i) neuroscientists and clinical neurophysiologists who want to check their system's or equipment's performance, operation and calibration, (ii) biomedical engineers and neuroscientists developing neuroelectric signal-processing systems and algorithms, (iii) neurologists and biomedical engineering instructors who need a practical signal generator to demonstrate modern electrodiagnosis methodologies and the operation of complex medical equipment, (iv) technicians who do corrective and pre-emptive maintenance of this complex equipment.

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References


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