INSTRUMENTATION & TECHNIQUES

A clock pulse generator (CPG) for behavioral time research*

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A device is described which (1) generates very accurate time calibration tones suitable for tape recording along with experimental behaviors, and (2) creates from such a recorded tone an easy-to-read structured pulse train for oscillographic tracings. Calibration tones at 1-, 5-, and 10-kHz pulse rates are derived from a crystal oscillator module and are made available for tape recording at one output of the device. The second output produces a four-level structured pulse train in which there is one pulse for each cycle of the calibration tone (every 10th is a little larger, every 100th a little larger yet, and every 1,000th larger still). An example of the use of this device in speech, timing research is given.

In studying the relationship between physical and behavioral time, an E must often record, along with the behavior of interest, a time standard for later reference. A second, less common need in research is the generation of a structured, highly readable timing trace. In our work, for example, we often wish to measure, to the nearest 0.01 sec (csec), the duration of a spoken paragraph that lasts a minute or more. It would be hard to avoid human errors in counting more than 6,000 cycles of a 100-Hz calibration tone, and the value of the time standard's accuracy might well be lost in such measurement error. A structured timing trace, in which every 10th pulse is larger and every 100th larger yet, would reduce both counting and eye strain, so that errors would seldom occur.

The clock pulse generator (CPG) described here was designed as a portable, low-cost device to generate both an accurate time standard and a timing trace that was easy to read, for use in research on temporal phenomena.

GENERAL SPECIFICATIONS OF THE CPG

For any calibration tone, specifications must be provided for frequency, waveform, and amplitude; for a

structured pulse, we must also know the number of levels to its structure.

The desired frequency of the calibration tone depends upon two factors, the nature of the experiment and the recording equipment. A frequency at least one order of magnitude higher than the highest data frequency to be encountered insures that measurement error will be less than 1% of the total variance. Thus, if differences of the order of milliseconds are experimentally important, then a 10-kHz calibration tone should be used; expected differences of the order of seconds require only a 10-Hz tone. Different recording devices accept different ranges of frequencies: some oscillographs and FM tape recorders accept dc to around 100 Hz, while others accept much higher frequencies. Standard audio tape recorders, on the other hand, usually accept frequencies between 100 and 10,000 Hz. Since some of our work involves differences on the order of milliseconds and often centiseconds, and since our FM tape recorder has an upper frequency limit of 5 kHz, the calibration circuitry of the CPG produces 1-, 5-, and 10-kHz tones. The 1- and 5-kHz tones can be recorded on our FM tape recorder, and all three frequencies on standard audio tape.

The waveform of the CPG calibration tone is square and requires filtering to avoid high-frequency ringing on both FM and direct tape recording. This filtering need not produce a sine wave, but only a waveform that on playback has one local maximum per cycle, which can then be used to trigger the CPG's input circuitry. Bandpass filtering (Krohn-Hite, Model 3100) at the fundamental frequency produces a signal acceptable for recording.

The output square wave switches between 0 and +4 V, yielding, after filtering, an approximate sinusoidal ± 1 -V signal. This level is acceptable to most recorders, but may be modified by amplification or attenuation, as needed.

The frequency of the structured pulse may be specified in either of two ways with the CPG. For real-time applications, it may be derived from the internally generated 1-kHz pulse rate. That is, the 1-kHz crystal oscillator output, in addition to appearing at the calibration tone output jack, also may be routed to the divider circuitry of the structured pulse network. Furthermore, the 1-kHz rate may be inhibited, in a manner to be described later, leaving a pulse train of 100 Hz and slower frequencies. The second, and more usual, way of determining the frequency of the structured pulse is by means of a prerecorded external signal. For example, we might originally record a 5-kHz

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Fig. 1. Example of four level structured pulse train, derived from a 100-Hz sine wave input to the CPG. Pulse heights are as described in the text.

Fig. 2. Block diagram of the CPG. R_1 , R_{10} , R_{100} , and R_{1000} are the summing resistors associated with the pulses occurring at the original (input) frequency, f , and its three submultiples, respectively; R_F is the feedback resistor of the op amp. Resistance values are discussed in the text and shown in Fig. 3.

calibration tone on FM tape and then play the signal back at 1/8 speed, yielding a structured pulse frequency of 625 Hz. The value of the CPG lies in the fact that, no matter how the original recording is temporally altered, the calibration tone is similarly changed and true time is preserved.

The structured pulse should have a waveform that promotes easy measurement and yet is within the capabilities of the oscillograph to produce. For example, rectangular waveforms have extremely fast switching times, appearing as discontinuities that are easy to locate unambiguously, unlike the peaks or zero crossings of a sinusoid; however, an oscillograph must have good frequency response in order to follow these transitions without excessive over- or undershoot. Our oscillograph (Elema-Schönder Mingograph, Model EM34) has a flat frequency response to nearly 1 kHz, permitting us to record fast pulses quite successfully. But the pulse duration must be less than the shortest interpulse interval, 1 msec in our uses. We have, therefore, chosen a pulse duration of 0.8 msec. This pulse duration yields an easily located vertical line on the output trace whenever there is a timing pulse at the input to the divider circuitry.

The amplitude of the output pulse also depends partly upon the characteristics of the oscillograph, but peak values in the range of 0.1-10.0 V satisfy most recording devices. The CPG produces pulses ranging in amplitude from 0.5 to 7.0 V, depending upon structure level.

The most important characteristic of the structured pulse is its number of levels. It is not unusual in published research to find two-level calibration traces, with one pulse every millisecond, but every 10th pulse a little larger, providing an easy-to-read centisecond trace. Our research involves events whose order of magnitude ranges from milliseconds to minutes; so our trace has four levels, as shown in Fig. 1. That is, the CPG can produce pulses at the rate of 1,000/sec, every 10th being a little bigger, every 100th larger yet, and every 1,000th even bigger. Since we do not always require four levels of structure, the highest and lowest levels can be independently inhibited from appearing at the output. Only the levels needed for necessary accuracy and easy reading need be used at any time.

APPARATUS

A block diagram of the CPG system is shown in Fig. 2, and a detailed schematic diagram appears in

Fig. 3. Schematic diagram of the CPG. Two-input logic gates: Type SN7400. Three-input logic gate: Type SN7410. All resistors: $\frac{1}{4}$ W, 5% tolerance. Input diode: Type 1N458.

Fig. 3. There are four basic components: the calibration tone generator, the divider circuitry, the external input circuitry, and the structured pulse output circuitry.

Calibration Tone Generator

The heart of the calibration tone generator is a crystal oscillator module (Digital Equipment Corporation, M404), from which may be obtained 11 different square-wave outputs that range in frequency from 5 kHz to 2 MHz. The module requires a +5 V dc power supply and is stable to less than 0.01% error between 0 and +55°C. As noted earlier, we employ the 5- and 10-kHz frequencies directly from the module and divide the 10-kHz frequency by 10, using a decade divider (SN7490), to obtain a 1-kHz tone. These three tones are applied to NAND Gates 5-7, whose other inputs are from Front Panel Switch SW-1 and NAND Gates 2-4, with normally LOW (0 V dc) output logic levels. Selecting a given position on SW-1 causes the associated NAND gate output to go HIGH (+5 V dc), permitting the signal to pass through one of Gates 5-7, although it becomes inverted. The outputs of Gates 5-7 are then connected to a three-input NAND gate (8). Two of these inputs are normally HIGH, since they are the inverse of the front panel switch settings. The tone therefore passes through Gate 8, with the original phase restored. The output of Gate 8 is routed directly to a front panel jack for connection to an external filter or recorder. The output impedance is approximately 120 ohms.

A low-pass filtering stage may be added between the three-input NAND gate and the front panel jack, so as to avoid using a separate filter when recording. The cutoff

frequency of this filter would, of course, have to be switched to correspond to the tone frequency.

Divider Circuitry

The divider circuit is simply three decade dividers (SN7490) in series, each of whose output is a symmetrical square wave having a frequency 1/10th that of its input. The input may be derived either from the 1-kHz tone or from the external input circuit; selection is made by means of SW-1 and NAND Gates 1 and 9, the signal is admitted through Gate 10, and its polarity is reversed by Gate 11. Pulse cycles are counted with respect to negative, i.e., HIGH to LOW, transitions, and the output of each divider is connected to a monostable multivibrator (one-shot), where it produces a pulse. The input to the first divider stage and the output of the last stage, representing the input frequency and 1/1,000th of the input frequency, may be independently inhibited from reaching their one-shots by means of front panel toggle switches, S-2 and S-3, and NAND Gates 12 and 13.

External Input Circuitry

Any repetitive waveform with a single local maximum in the range of +0.1 to +40 V may be used to trigger the external input circuitry. The input signal is applied to one input of an LM311 comparator, through a 1-K-ohm resistor, the other input acting as a reference voltage adjustable through the range of 0.0 to 1.0 V. Whenever the input voltage exceeds the adjusted voltage, the LM311 goes to a HIGH state; otherwise it remains in a LOW state. A small amount of feedback (40 mV, through a 10-K-ohm resistor) promotes stability of firing

and clean transitions in the LM311, and a 1.0-microF capacitor in the voltage divider network serves to reduce ripple in the reference voltage.

Because of the adjustable threshold, complex waveforms with more than one local maximum per cycle could be used as input signals. For example, if there is just one absolute maximum, and if this absolute maximum is greater than 0.1 V, then the threshold may be set below the absolute maximum and above the other maxima, permitting the LM311 to fire just once per cycle. Thus, a waveform, such as a damped sinusoid produced by recording a square wave on direct tape, could in fact be used successfully to trigger this external input circuitry if the amplitude of the input can be adjusted sufficiently.

Although the LM311 can tolerate large positive voltages, it misfires in the presence of large negative swings. Since many external signals are symmetric sinusoids, a diode is added at the input of the LM311 to clip the negative peaks at approximately -0.8 V.

Output Circuitry

The outputs of the one-shots associated with the four submultiples of the input frequency are rectangular pulses whose duration is determined by an associated RC network. This duration is 0.8 msec in the CPG. By simply scaling and adding these four different pulses at the summing junction of an operational amplifier (op amp), we obtain a suitably structured pulse train. That is, for each cycle of the input signal, one pulse is produced at the output of the one-shot associated with the input frequency ($\div 1$ one-shot); the amplitude of this pulse is determined by the ratio between the value of the resistor joining the $\div 1$ one-shot to the op amp and the op amp's feedback resistor value. For every 10 cycles of the input signal, one pulse is produced at the output of the $\div 10$ one-shot; the amplitude of this pulse is also determined by the ratio between the resistor value joining this one-shot to the op amp and the feedback resistor value. The two pulses add, since they occur at the same time, producing a summed input to the op amp. Similarly, the $\div 100$ - and $\div 1,000$ one-shots produce pulses every 100 and 1,000 cycles, respectively, and these pulses are added at the op amp input when they occur. The largest summed pulse is produced when all four one-shots fire together, that is, every 1,000 cycles; the smallest pulse is produced when only the $\div 1$ one-shot fires. The exact values of the pulse amplitudes at the output of the op amp are given by the following equations:

$$V_1 = 5 \times R_F (1/R_1)$$

$$V_{10} = 5 \times R_F (1/R_1 + 1/R_{10})$$

$$V_{100} = 5 \times R_F (1/R_1 + 1/R_{10} + 1/R_{100})$$

$$V_{1000} = 5 \times R_F (1/R_1 + 1/R_{10} + 1/R_{100} + 1/R_{1000})$$

where V_1 = smallest pulse amplitude (volts); V_{10} = next bigger pulse amplitude; V_{100} = next bigger pulse amplitude; V_{1000} = biggest pulse amplitude; R_F = feedback resistance (ohms); R_1 = resistance joining $\div 1$ one-shot to op amp; R_{10} = resistance joining $\div 10$ one-shot to op amp; R_{100} = resistance joining $\div 100$ one-shot to op amp; and R_{1000} = resistance joining $\div 1,000$ one-shot to op amp.

We have chosen resistance values such that $V_1 = 0.5$ V, $V_{10} = 1.0$ V, $V_{100} = 2.5$ V, and $V_{1000} = 7.0$ V. These values are all within the recording range of most oscillographs and yield a structure that is easy to read.

Note again that the $\div 1$ frequency, corresponding to the input, and the $\div 1,000$ frequency may be inhibited from contributing to the output trace. With the $\div 1$ pulses removed, the remaining pulses are 0.5 V smaller in amplitude; with the $\div 1,000$ frequency removed, the 7.0-V pulses do not appear in the output.

The op amp is the final output stage, and op amps differ in their ability to reproduce the rectangular pulses from the one-shots. Since our oscillograph has a good frequency response, we have chosen an op amp (MC1439) that, because of its high slew rate (34 V/microsec), will follow the pulses faithfully. This op amp has a high output impedance (4-K-ohm), so our device should be used with external load impedances of 10 K ohm or greater. The object of the CPG is the generation of a visually satisfactory trace. Thus, there is no reason why other op amps cannot be used in conjunction with other oscillographs, depending upon frequency requirements.

The cost of the CPG is approximately \$110, plus fabrication costs.

ILLUSTRATIVE EXAMPLE

Our work on the control of timing in speech production (Allen, 1973) involves measuring the durations of certain phonetic intervals in each of several repetitions of a given speech sample. Because the accuracy with which a speaker times his utterance is contaminated by uncontrollable changes in speaking rate, we must keep track of the exact time at which each repetition occurs. For example, Fig. 4 shows oscillographic tracings of the first and last of a series of 30 spoken repetitions of the sentence "Say the word 'pop' again." During the recording of these 30 repetitions, the 1-kHz CPG calibration tone was recorded on the other track of the tape, and on subsequent playback, this recorded tone served to trigger the input circuitry of the CPG, producing the three-level structured pulse trace in Fig. 4. Because the $\div 1$ pulses were inhibited in this trace, the smallest pulses are 0.01 sec apart, and the largest pulses occur every second. As may be noted from Fig. 4, the last 1-sec pulse before the first repetition is labeled "0," with subsequent 1-sec pulses numbered in order. The entire 30 repetitions therefore took approximately 71 sec to produce.

Fig. 4. The first and last of 30 repetitions of the phrase "Say the word 'pop' again." Upper trace: speech wave. Center trace: rectified, integrated, and smoothed speech wave (time constant = 6 msec). Lower trace: three-level structured pulse derived from originally recorded 1-kHz calibration tone; the ± 1 pulses have been inhibited and do not appear in the trace, and the $\pm 1,000$ pulses are labeled. The vertical lines are explained in the text.

Vertical lines have been drawn at the vowel onsets of the syllables "Say," "pop," "a-," and "-gain," since we have shown previously (Allen, 1972) that vowel onsets are valid indicators of rhythmic loci in speech. The times of occurrence of these four vowel onsets may be determined by the point at which the vertical lines intersect the timing trace and are 0.21, 0.77, 0.99, and 1.13 sec and 70.14, 70.70, 70.89, and 71.05 sec after the "0" pulse for the first and last repetitions, respectively. There is, of course, measurement error associated with deciding where to draw the vertical line and with actually drawing the line. But there is

essentially no time error associated with tape recording, playback, and oscillographic writeout, thanks to the CPG.

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