INSTRUMENTATION & TECHNIQUES

A pseudorandom noise generator for use in auditory research¹

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A noise generator that is capable of delivering long-duration samples of reproducible noise is described. The noise is generated as a pseudorandom telegraph waveform but may be filtered so that its amplitude distribution is approximately Gaussian. The design and construction of the generator are detailed and a few possible applications are given.

Some experiments in audition require that the noise (masking) signal be repeatable. Several Es (Sherwin et al, 1956; Green, 1964; and Ahumada, 1967) recorded acoustical stimuli on magnetic tape for repeated presentations. The number of different sequences of experimental trials is usually small, since a new tape must be prepared for each sequence desired. Also, this method suffers from poor signal-to-noise ratio, interchannel cross-talk, and amplitude and frequency distortion introduced by the playback system.

Repeated conversions of a set of random sample points into an analogue signal produce identical masking signals. For example, Pfafflin and Mathews (1966) produced repeatable noise using two digital computers. Sets of random sample points were generated by a large computer and stored in the smaller one for conversion to analogue form. Raab and Leshowitz (1968) used an average-response computer to "freeze" a noise waveform for repeated presentations. Their approach eliminates the need for a large computer; however, only one waveform can be "frozen" at a time. Thus, an E cannot select his noise waveform from a predetermined set.

This article describes a pseudorandom noise generator that can be built from standard digital logic cards at a cost much less than that of the smallest digital computer. The noise generator can be used alone in laboratories without digital computers, but its utility is increased when

it is interfaced to a small digital computer.

Figure 1 shows the block diagram of the pseudorandom noise generator. It is based upon a design suggested by Korn (1966). This device generates a pseudorandom telegraph waveform (RTW). The RTW is a symmetrical binary waveform with randomly distributed zero crossings (Rice, 1954; Blackman, 1966). The output voltage must remain at one of its two allowed levels for a period of time, Δt , then, at the end of each Δt interval, it may change to the alternate level with probability equal to one-half. The zero crossings are determined by a 25-bit shift register rather than by a truly random source. A special feedback network has been added to the shift register so that it produces a maximum length, pseudorandom sequence (Birdsall & Ristenbatt, 1958; Golomb, 1964, 1967; Korn, 1966).

The feedback network contains an exclusive-OR circuit which introduces a 1 (one) into the input of the shift register if either the final stage or the third stage contains a 1. If both contain 1s, or both contain 0s (zeros), then a 0 is introduced at the input. The choice of stages tested by the feedback network is based upon properties of shift-register sequences which are discussed in Birdsall and Ristenbatt (1958) and Golomb (1967). These authors show that such a feedback connection will cause the shift register to pass through $(2^{25} - 1)$ states before repeating. The all-zero state is forbidden because the shift register cannot escape from it.

An adjustable clock is used to deliver periodic shift pulses to the shift register. The time between clock pulses (i.e., its period) determines Δt for the pseudo-RTW. Thus, if the clock rate is 10 kHz, the shift-register sequence is periodic with period $T \approx 0.9$ h.

Before the first shift pulse occurs, the shift register is in an initial state. This initial state may occur serendipitously or it may be introduced by loading into the shift register a bit pattern established in the switch register. Since the maximum length sequence is deterministic, a pseudorandom waveform will be reproduced exactly each time the shift-register begins from a given initial state.

Figure 2 shows the circuit diagram for the pseudo-RTW generator. The entire device was constructed from 16 Digital Equipment Corporation logic modules which were mounted in a standard 19-in. module bay. All of the switches and input or output jacks were mounted on a 3-in. front panel.

In Fig. 2, the first 24 flip-flop stages (0 through 23) are arranged into three columns of eight each only for convenience in drafting. The final stage (FF24) is shown immediately to the right of these columns. Below it is the exclusive-OR feedback circuit. Beneath the feedback circuit is the variable clock which delivers shift pulses to the shift register whenever FF25 is in the "on" state. This flip-flop may be controlled manually by using pushbuttons located on the front panel. Input jacks are also provided so that any externally supplied ground can enable or disable the clock. The clock rate is determined by selecting a combination of R and C on the clock card.

In addition to the common shift-pulse line to each flip-flop, two other common lines are shown. One, the clear line, sets the device to the all-zero state and disables the clock. After entering the clear state, an initial state must be loaded into the shift register before a RTW can be generated. To load the shift register, those flip-flops that are to contain a 1 are set by collector triggering. The 0 side of each flip-flop,

Fig. 1. Block diagram of a pseudorandom noise generator. (From a design suggested by Korn, 1966).

Fig. 2. Schematic diagram of a pseudo-RTW noise generator. The symbols are a locally modified version of DEC's negative-level logic symbols.

except for the final one, is connected to a load line through a switch and a diode. If a switch is closed (as all of them are in Fig. 2), then its flip-flop will be set (i.e., it will contain a 1) when the load line is grounded. Those stages not connected to the line are unaffected; thus, loading an initial pattern is a two-step process. First, the device is cleared to the all-zero state, then the bit pattern established in the switch register is loaded. Notice that the final stage has no corresponding switch. This was done to ensure that all zeros could never be loaded as an initial state. Both pushbuttons and input jacks are provided for the load and clear functions.

The dual flip-flop cards (R205) that were used in the shift register contain an added gate on the 1 side of each flip-flop. These gates may be used to load the initial pattern from a laboratory computer. For a 12-bit machine, two 12-bit transfers would be required, but interfacing would not be difficult.

To produce a repeatable noise waveform

with an approximately Gaussian amplitude distribution, the pseudorandom waveform must first be centered about 0 V and then low-pass filtered. The level amplifier shown in Fig. 2 is used to shift the 0- and 3-V levels of the shift register to symmetrical voltage levels, either ± 3 or ± 6 V. Then a simple RC, low-pass filter with $\Delta t < \tau < n\Delta t$ (here $\tau = RC$, $n = 25$) transforms the bimodal amplitude distribution of the RTW waveform into one that is approximately Gaussian (Korn, 1966). This is based upon empirical rather than analytical findings, since an analytic solution for the amplitude distribution of the pseudo-RTW has not been derived. However, solutions for the distribution of true RTW noise after simple RC low-pass filtering show that its first-order density function does approximate the Gaussian for some values of τ (McFadden, 1959a, b; Wonham & Fuller, 1958).

Figure 3a shows an amplitude histogram for the low-pass filtered pseudo-RTW noise, and Fig. 3b shows a comparable

Fig. 3. (a) Amplitude histogram of the pseudo-RTW noise at the output of a simple RC low-pass filter. (b) Amplitude histogram of thermal noise equal in rms voltage to the filtered pseudo-RTW noise, above.

Fig. 4. Additional circuitry needed to generate pseudorandom pulse trains.

amplitude histogram for a thermal noise. Visual inspection of Fig. 3 shows no obvious differences between the pseudorandom and thermal noise distributions; however, one must realize that these histograms emphasize the behavior near the mean value while providing little information about the tails of the distributions. With this limitation in mind, we assert that the amplitude distribution of the pseudorandom noise approaches the Gaussian with no greater error than for thermal noise.

This noise generator may also be used to generate pseudorandom sequences for stimulus presentations in automated experimental apparatus. If the automated apparatus is driven by logic circuitry compatible with the DEC logic used here, no special interfacing is required. At most, simple level conversions must be performed. In addition to its use as a signal generator, this device may be used to program stimulus presentations for a number of nonauditory experiments. The unfiltered output can be used directly if the logic circuitry is compatible with the DEC logic used here. Again, only simple level conversions are required. The number of repeatable pseudorandom sequences is, of course, $2^{25} - 1$, the number of different initial states. In addition,

trial-by-trial information is easily recovered.

Figure 4 shows a simple modification to the device that allows the generation of pseudorandom unipolar or bipolar (alternate) pulse trains.³ Only four additional logic cards are required to implement this modification, since the level converter is the one used in the original device. The outputs are independent with respect to the toggle-switch positions. Thus, both a pulse train and a correlated RTW are generated simultaneously. These pulse trains may then be used as signals or maskers in auditory experiments.

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NOTES

1. This paper describes a device that was constructed for auditory research that was subsequently submitted to the University of Pittsburgh in partial fulfillment of the requirements for the PhD. The research was supported by grants from the National Institutes of Health awarded to Robert C. Bilger. The author was supported by a fellowship from the Rehabilitation Services Administration.
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3. This modification was suggested by Richard V. Wolf who also was of immeasurable aid in the design and construction of the original device.