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A DETERMINISTIC BROAD-BAND SIGNAL FOR ACOUSTICAL MEASUREMENTS

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INTRODUCTION

When Schroeder and his colleagues [1] first introduced the use of the pseudorandom sequence (M-sequence), they were primarily interested in the precision measurements of impulse responses in halls. Using the impulse response, the Reverberation Time, the Modulation Transfer Function, and the Speech Transmission Index can be estimated. This signal has been used for other acoustical measurements in our laboratory. In this paper, we will present a brief review of its generation, properties, implementation with digital processing, and applications.

GENERATION

A simple pseudorandom sequence can be generated by a feedback shift register arrangement shown in Fig. 1. The m bits shift register is clocked at some fixed frequency f_c . An EXCLUSIVE-OR gate (otherwise known as modulo-two adder), is used to generate the feedback signal from the combination of the n th bit and the last(m th) bit of the shift register. The circuit goes through a set of states repeating itself after L clock pulses. If m and n are chosen correctly, the shift register will go through the maximum number of allowable states ($2^m - 1$) before repeating itself. For certain values of m , more than one feedback loop will be required (see Ref. 2 for an exhaustive list of the possible arrangements).

PROPERTIES

There are three properties of the pseudorandom sequence that need to be addressed here. First, it is periodic and deterministic. Secondly, if the binary states are chosen to be +1 and -1, the autocorrelation function of a pseudorandom sequence is always 1 for zero shift and drops to $-1/L$ for any other shift, repeating after each period of the sequence. The corresponding power spectrum is a line spectrum as shown in Fig. 2, whose upper 3-dB roll-off point is about $0.45 f_c$. Hence, by adjusting the clock frequency, one can adjust this flat broad-band signal over a very wide frequency range. Since the binary wave-form switches between the same two amplitude

levels, its rms value, and therefore its total power, is not affected by a change of band-width. These two properties are important for acoustical measurements. For linear time invariant systems, one period of the signal is sufficient and no ensemble averaging will be required. Averaging can still be applied, of course, to reduce the system noise. Thirdly, if a window of width m is slid along a pseudorandom sequence, each of the $2^m - 1$ non-zero binary m -tuples is seen exactly once. This property provides an easy way of checking that the pseudorandom sequence is properly generated.

DIGITAL PROCESSING

There are two methods of data processing depending on the applications. For frequency response measurements, it is most convenient to use the fast Fourier transform (FFT). However, the FFT algorithms need the total number of data points to be a power of 2 whereas the sequence length L is equal to $2^m - 1$. This mismatching problem has been discussed by Chu [3] who also provided a simple and practical method to resolve this difficulty.

The other method is to use the cross-correlation technique to compute the impulse response as illustrated in Fig. 3. It is well known that the input-output cross-correlation, R_{iO} , of a linear system under white noise excitation is proportional to the system impulse response, h [4]. Since the pseudorandom sequence has an approximately flat spectrum, it can be considered as a white noise input if its frequency range is higher than the upper frequency limit of the system under test. If the output s_0 is sampled at the clock rate of the sequence, one has in matrix form the following relationship,

$$[h] = L^{-1} [M] [s_0] \quad (1)$$

where $[M]$ is a $L \times L$ matrix containing the right circularly delayed version of the sequence $M(\cdot)$. Because the elements of $[M]$ are all ± 1 , only additions and subtractions are required to perform the matrix multiplication and Schroeder (see Ref. 5) was first to observe that a fast computation of $[M][s_0]$ was possible using the techniques developed in Hadamard spectroscopy. The techniques involve finding the permutational equivalence $[M] = [P][H][Q]$ between the M -sequence transform matrix $[M]$ and the Sylvester-type Hadamard matrix $[H]$ such that the fast Hadamard transform can be applied to obtain a fast M -sequence transform [6,7,8,9,10]. Specific recipes for constructing the permutation matrices $[P]$ and $[Q]$ can be found in References 5, 9, and 11.

APPLICATIONS

An application of the pseudorandom sequence was given in Ref. 12 for the determination of the room responses in a reverberation chamber for the cases with and without a rotating diffuser. The procedure can replace the single frequency sweep method in the qualification test for pure-tone or narrow-band sound power measurements with significant saving in testing time.

Another important application of the pseudorandom sequence was reported in References 13 and 14. With this signal, it is possible to replace the two microphones with a single microphone in the intensity technique for broad-band sound transmission loss, sound absorption measurements in reverberation rooms, and for impedance measurements in an impedance

tube. This single microphone method eliminates errors associated with the instrumentation phase mismatch mutual interference of the microphones, and uncertainty regarding the effective separation distance of the microphones.

The cross-correlation technique has also been implemented in our laboratory (based on the recipe given in Ref. 9) for impulse response and decay measurements. Because of the lack of correlation between the pseudorandom sequence and any background noise that might exist in a room, this technique provides a possibility for measuring reverberation time in construction sites or in factories during normal operations. Preliminary results are encouraging. Figure 4 shows an impulse response measured in a reverberation room where the source signal was only 20 dB above a high background noise deliberately introduced into the room by a radio set. The source signal was a pseudorandom sequence of length $L = 2^{14} - 1$ generated by a digital shift register at a clock rate of 8 kHz. The corresponding decay curve obtained from the impulse response using Schroeder's integrated-impulse technique [15] is shown in Fig. 5, which compared well with the decay curve determined by the decay-curve-averaging method [15] with the background noise turned off. Fifteen averages were used in the decay-curve-averaging method whereas only one impulse response was used by the integrated-impulse technique. Improvement to the dynamic range of the integrated-impulse technique can be achieved by averaging a number of impulse responses before the decay curve is computed.

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FIGURE 1
PSEUDORANDOM SEQUENCE GENERATOR USING SHIFT REGISTERS.

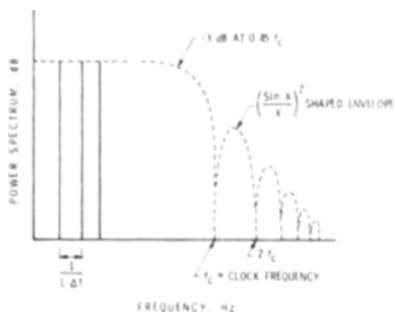


FIGURE 2
POWER SPECTRUM OF UNFILTERED MAXIMUM-LENGTH SEQUENCE GENERATED BY THE FEEDBACK SHIFT REGISTER. (SCHEMATIC ONLY; NOT TO SCALE)

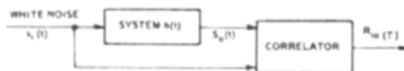


FIGURE 3
CORRELATION METHOD OF MEASURING THE IMPULSE RESPONSE

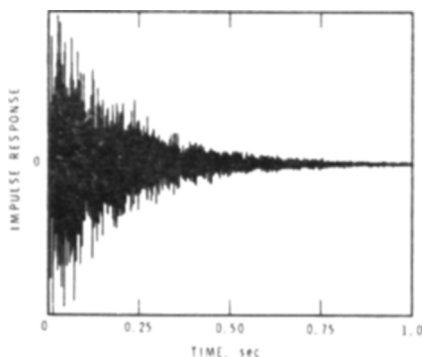


FIGURE 4
WIDE-BAND IMPULSE RESPONSE OF A REVERBERATION ROOM MEASURED WITH A PSEUDORANDOM SEQUENCE. ONLY 1 sec OF A 2.048 sec DATA SET IS SHOWN.

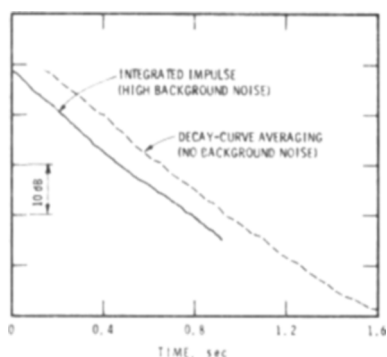


FIGURE 5
COMPARISON OF THE DECAY CURVE OBTAINED FROM THE IMPULSE RESPONSE OF FIG. 4 BY SQUARING AND INTEGRATING TO THAT OBTAINED BY THE DECAY-CURVE-AVERAGING METHOD