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**ARCHITECTURAL ACOUSTIC MEASUREMENTS USING PERIODIC
PSEUDORANDOM SEQUENCES AND FFT**

by W.T. Chu

ANALYZED

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RÉSUMÉ

La création, et certaines caractéristiques pertinentes, d'une catégorie de séquences périodiques pseudo-aléatoires appelée "séquence de longueur maximale", fait l'objet d'une courte description. Une méthode simple et pratique pour la résolution par la transformation rapide de Fourier d'un problème technique lié à l'utilisation de ces séquences, est décrite. Les avantages possibles de l'utilisation d'une séquence de longueur maximale comme signal d'essai dans les mesures acoustiques en architecture sont abordés et illustrés au moyen d'un exemple.

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Architectural acoustic measurements using periodic pseudorandom sequences and FFT

W. T. Chu

Noise and Vibration Section, Division of Building Research, National Research Council of Canada, Montreal Road, Building M-27, Ottawa, Ontario, Canada K1A0R6

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The generation and some relevant properties of a class of periodic pseudorandom sequences called the maximum-length sequence is described briefly. A simple and practical method is proposed to resolve a technical difficulty in using these sequences with FFT processing. The potential advantage of using a maximum-length sequence as a test signal for architectural acoustic measurements is discussed and illustrated by an example.

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INTRODUCTION

In acoustics, especially in architectural acoustics, pseudorandom sequences have been used primarily as a substitute for the conventional white noise generators employing gas discharge tubes or temperature-limited diodes. Although the pseudorandom sequence is a signal which looks and acts like random noise, it is in fact periodic and deterministic. That is, it has a repeated pulse pattern. Thus, under steady-state excitation, the output of a time invariant system will also be periodic and deterministic. As a result of the special characteristics of the source, no ensemble averaging will be required if exactly one period of data, taken from any segment of the time record, is used. (Averaging can still be applied, of course, to reduce the system noise.) This advantage can be obtained with modern digital signal processing. When the pseudorandom sequence is used in this manner, we will label it a periodic pseudorandom sequence. Such an application was overlooked in the field of architectural acoustics until the mid-seventies when Schroeder and his colleagues^{1,2} proposed some new measurement techniques. Since then, this test signal has not gained much popularity beyond the Göttingen group, with only a couple of exceptions.^{3,4}

In order to popularize this potentially very useful testing signal, we will present a brief description of its generation and some relevant properties, a simple and practical method to overcome a technical difficulty in using the sequence with the fast Fourier transform (FFT), and a few example applications. The advantage of using the sequences as a test signal for architectural acoustic measurements will be emphasized.

I. GENERATION

The most popular and simplest periodic pseudorandom sequence is generated by a feedback shift register arrangement shown in Fig. 1.⁵ 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. Since the shift register contains m stages, there is a maximum of 2^m

conceivable states. (However, the case of zeros in all the stages must be prevented to avoid a "hung up" situation.) If m and n are chosen correctly, the shift register will go through the maximum number of allowable states before repeating itself. Thus, the largest possible number of pulses in a repeated pattern at the output is $L = (2^m - 1)$; hence the name maximum-length sequence is also given to this periodic pseudorandom binary sequence. These m and n values are listed in Ref. 5. A few of them are shown in Fig. 1.

II. SPECTRUM OF THE BINARY OUTPUT

If the binary states are chosen to be $+1$ and -1 , the autocorrelation function of a maximum-length 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,⁵ the envelope of which is a $[(\sin x)/x]^2$ curve, as shown in Fig. 2. The harmonic spacing is a function of the sequence length L and the clock frequency f_c . It is equal to f_c/L or $1/L\Delta t$, where Δt is the clock period.

The upper 3-dB roll-off point is about $0.45 f_c$. Hence, by adjusting the clock frequency, one can adjust the upper 3-dB frequency over a very wide range.

It is interesting to note that regardless of what clock frequency or sequence length is selected, the binary waveform always switches between the same two amplitude levels. This means that its rms value, and therefore its total power, is not affected by a change of bandwidth. Conventional white noise generators do not have this property.

III. DIGITAL PROCESSING

An important advantage in using periodic pseudorandom sequences for testing linear time invariant systems is that, under steady-state excitations, the output is also periodic and hence deterministic. Only one period of data will be required for the experiment if it can be determined exactly. The data can be taken from any segment of the time record. This can be accomplished easily with digital processing. Thus if f_s is the sampling frequency and M is the total number of data points, the requirement for the analysis time will be

FIG. 1. Periodic pseudorandom sequence generator using shift registers.

EXAMPLE VALUES:

m	n	LENGTH
11	9	2047
15	14	32767
17	14	131071
18	11	262143

$$M/f_s = L/f_c. \quad (1)$$

Of course, the analysis time and hence the period chosen for the sequence has to be as long as the impulse response of the system under test.

For system response measurements, it is most convenient to use the fast Fourier transform (FFT).^{2,4} However, the FFT algorithms need M to be a power of 2 whereas $L = 2^m - 1$. Schroeder² suggests extrapolation from $(2^m - 1)$ to 2^m samples in the period but gives no details. Eriksson⁴ proposes another extrapolation scheme requiring a 2^{m+1} points transform which might be a disadvantage for smaller computers. Recently, Fasbender and Güngel⁶ suggested using two coupled clocks such that

$$f_s = [2^m / (2^m - 1)] f_c. \quad (2)$$

However, there is a simple and more practical method of resolving this difficulty, which will be presented in the following paragraphs.

Another way of looking at Eq. (1) is that the spectral resolution, f_s/M , of the FFT should be equal to the frequency spacing, f_c/L , of the periodic pseudorandom sequence.

FIG. 2. Power spectrum of unfiltered maximum-length sequence generated by the feedback shift register.

There is no need for f_s to be equal or close to f_c , but they have to be synchronized. Thus, it is possible to use a high clock frequency f_c and a lower sampling frequency f_s obtained from f_c by using digital dividers, so that the two different clock frequencies are synchronized. L and M can then be chosen accordingly to satisfy Eq. (1) as closely as possible.

Suppose a 2048-point FFT and a sampling frequency of 2048 Hz are chosen for a particular experiment. The spectral resolution will be exactly 1 Hz and the useful frequency range will be approximately 1 kHz as dictated by the Nyquist condition. To make f_c/L as close to 1 as possible, one would use a very high clock frequency and a long sequence. A factor of 16 larger than the sampling frequency is quite adequate for the clock frequency. For example, taking $f_c = 32\,768$ Hz, one can have $L = (2^{15} - 1)$ to give a 1.000 03-Hz frequency spacing for the noise source.

As shown in the examples given in the following section, this arrangement gives very good results up to 60% of the frequency range of the analysis. Since, in general, the useful frequency range of the FFT is about 80% of the range of analysis, very little useful information is lost. In principle, one can use a factor larger than 16 to increase the range. The choice, however, is limited by the availability of the maximum-length sequences. The next possible sequence is for $L = (2^{17} - 1)$ unless one uses multiple feedback systems other than the simple single feedback system presented here.

Recently, Alrutz and Schroeder,⁷ and Borish and Angell⁸ introduced another efficient method (called the fast Hadamard transform) for computing impulse responses using a direct cross-correlation technique. Unfortunately, there were no comments in either reference to any problems in computing the frequency response from the measured impulse response by FFT.

IV. EXAMPLES AND DISCUSSION

The periodic pseudorandom sequence has been used to determine the frequency response of a bandpass filter and the room response in a reverberation chamber of fixed geom-

etry. For comparison, the same responses have also been measured using a conventional single frequency sweep technique. Figure 3 shows a block diagram of the instrumentation. Values for the sequence length, the clock frequency, and the sampling frequency are the same as those discussed in the previous section. The frequency response is determined from the transfer function relationship; i.e.,

$$H(f) = G_{IO}(f)/G_{II}(f), \quad (3)$$

where $G_{IO}(f)$ is the cross spectrum between the input and the output and G_{II} is the auto-power spectrum of the input signal. These are obtained by FFT using 2048 data points each. Since one period of a periodic signal was used, no averaging or windowing is necessary in the data processing.

Figure 4 shows the power spectrum of the input signal. Results indicate that up to at least 60% of the analysis range, the true spectral content of the periodic pseudorandom sequence has been determined correctly. The same conclusion can be drawn from Fig. 5 where the frequency response of a bandpass filter obtained by the single frequency sweep technique (solid curve) is compared with that obtained by the present method (dashed curve). The large spike at the low-frequency end is the 60-Hz pickup.

Although the reverberation chamber is a multimodal system, the room responses obtained using a periodic pseudorandom sequence compared very well with those obtained by the single frequency sweep method. The responses obtained are actually for a combination of the power amplifier, the speaker, the reverberation chamber, and the microphone system. With the same test signal and the same analysis procedure, only responses below 60% of the frequency range of the analysis will be presented.

Figures 6 and 7 compare results in two frequency ranges. The solid curves depict the responses obtained by the

FIG. 3. Block diagram of experimental setup for response measurements using periodic pseudorandom sequence.

FIG. 4. Measured power spectrum of the filtered maximum-length sequence.

single frequency sweep technique and the dashed curves represent responses determined by the present method. The minor differences are mainly caused by environmental variations such as changes in room temperature. The single frequency sweep test took more than an hour to complete 200 single frequency measurements. Data acquisition using the periodic pseudorandom sequence took only 1 s and provided 600 useful results!

This last example, in which the sequence was effectively used as a deterministic multitone signal, reveals the tremendous advantage of using a periodic pseudorandom sequence for architectural acoustic measurements. This has important applications in qualification tests for narrow-band sound power measurements⁹ as suggested by Chu.³ Recently Chu¹⁰ has demonstrated a way of performing large FFTs on mini-

FIG. 5. Comparison of the frequency responses of a bandpass filter centered at 400 Hz obtained by two different methods.

FIG. 6. Comparison of the room responses obtained by two different methods in the range of 180–280 Hz.

FIG. 7. Comparison of the room responses obtained by two different methods in the range of 445–545 Hz.

computers. Thus there are hopes that the time-consuming qualification tests can soon be accomplished in minutes rather than in hours. A full report on qualification tests using a periodic pseudorandom sequence will be published later.

Other frequency resolutions can be obtained by changing the clock frequency or the length of the sequence. If the clock frequency is changed but the length of sequence and the clock to sampling frequency ratio are kept fixed at $(2^{15} - 1)$ and 16, respectively, experimental results show that the 60% rule still holds. In other cases the exact range of applicability must be redetermined from the measured power spectrum of the sequence.

V. CONCLUSION

A brief description on the generation and some relevant properties of a class of periodic pseudorandom sequences, called the maximum-length sequence, have been presented. A simple and practical method has also been proposed to resolve a technical difficulty in using the sequence as a test signal together with digital FFT processing. An example of applying the sequence as a test signal for determining the room response of a reverberation chamber reveals the potential advantage of using the sequence for architectural acous-

tic measurements. In fact, it would also be useful for other branches of acoustics and vibration testing.

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