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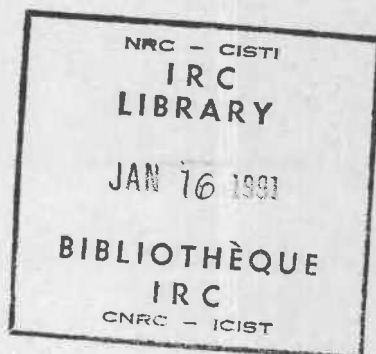
Impulse-Response and Reverberation-Decay Measurements Made by Using Pseudorandom Sequence

by W.T. Chu

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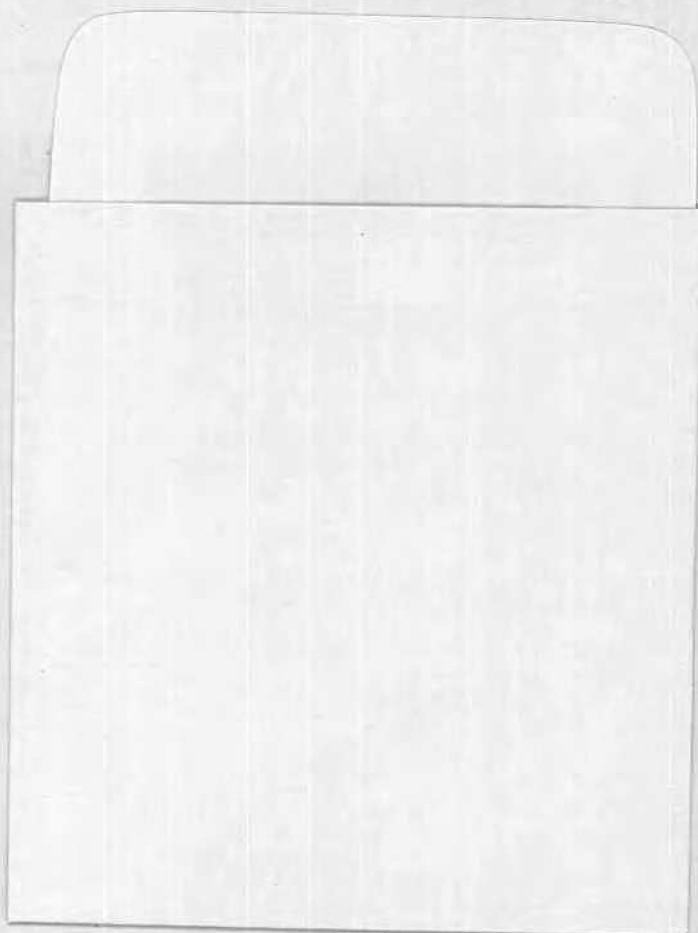
Résumé

L'auteur expose de façon détaillée la méthode de corrélation croisée comportant l'utilisation d'une séquence pseudo-aléatoire périodique de mesures de la réponse en impulsion et de l'affaiblissement de la réverbération. Il présente aussi les résultats d'expériences visant à montrer que cette méthode permet d'effectuer des mesures dans un environnement très bruyant.

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Impulse-Response and Reverberation-Decay Measurements Made by Using a Periodic Pseudorandom Sequence

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ABSTRACT

A detailed account of the cross-correlation method involving the use of a periodic pseudorandom sequence for impulse-response and reverberation-decay measurements is presented. Experimental results are also provided to demonstrate the potential of this method for making measurements in a very noisy environment.

INTRODUCTION

The most fundamental physical descriptor in room acoustics is the impulse response between a source and a receiver position in the room. All the acoustical measures for subjective evaluations of rooms, including reverberation time, can be derived from the impulse response. With the advent of microcomputers and digital-signal processing, more efficient and accurate techniques for measuring impulse responses become feasible. A general review of both the conventional and the modern techniques has been given by Otshudi, Guilhot, and Charles.¹

Among the modern techniques, the one originated by Schroeder and his colleagues at Gottingen^{2,3} has gained widest acceptance by acousticians^{4–8} and, in this author's opinion, is the most powerful method available. The technique uses a periodic pseudorandom sequence (also known as a maximum-length sequence or *m*-sequence) as the source signal, and the impulse response is determined by a cross-correlation method based on

techniques developed in Hadamard spectroscopy. Since this technique effectively uses a very large number of pulses limited only by the length of the sequence chosen, it offers a significant improvement of the signal-to-noise ratio. In addition, the cross-correlation process minimizes the influence of background noise. With adequate averaging, it is possible to use signal levels that are significantly below background-noise level, making this technique very useful for acoustical measurements in auditoria, offices, factories, or construction sites. Computer plug-in boards and software for implementing this measuring technique are now commercially available.

An understanding of the method, including the special signal processing involved, is essential for proper utilization (or to design one's own system). However, a simple and coherent treatment of the subject is lacking in the acoustical literature. In this paper, a review of the basics will be given, together with examples of measurements in a simulated noisy environment.

Problems related to characteristics of the source driver, the receiver, and any intervening electronics on the 'fidelity' of the measured impulse response will not be addressed here. As suggested by Kuttruff,⁹ this should not be an important issue for reverberation-decay measurements in rooms of simple shapes if an omni-directional receiver is used. This is certainly the case for most residential and industrial noise-control applications.

IMPULSE RESPONSE BY CROSS-CORRELATION

According to random-noise theory,¹⁰ the input-output cross-correlation, R_{i_o} , of a linear time-invariant system under white-noise excitation is proportional to the system impulse response, $h(t)$ (Fig. 1). The technique proposed by Schroeder and his colleagues involves replacing the random noise with an m -sequence. An m -sequence is a periodic binary sequence that has an approximately flat spectrum, and it can be generated fairly simply by a feedback arrangement of shift registers. Its periodic length, n , is equal to $2^m - 1$, where m is the number of stages used in the shift-register arrangement. A detailed discussion about its generation and properties has been given elsewhere by the present author.⁸

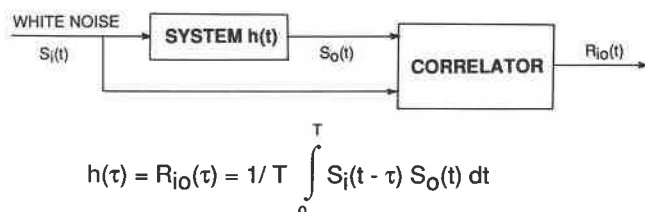


Fig. 1. Cross-correlation method for measuring impulse response.

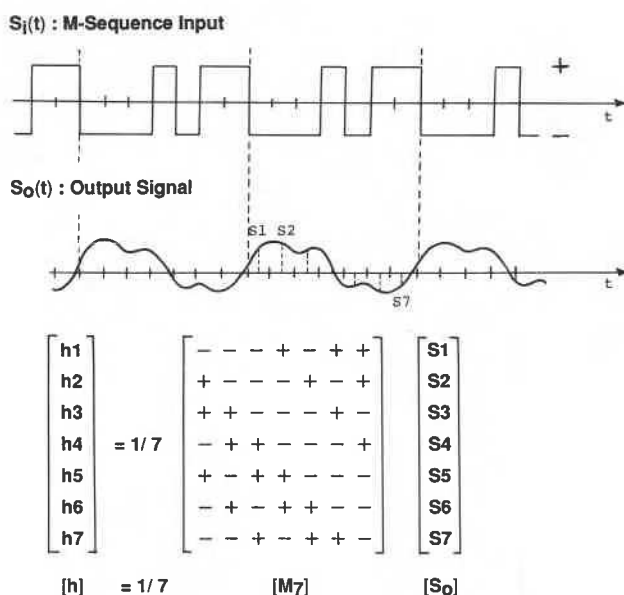


Fig. 2. Example of a matrix representation of the cross-correlation method with an m -sequence used as the input signal.

Figure 2 shows an example of an m -sequence of length 7 as the input signal S_i and a hypothetical output signal S_o . Since the m -sequence is periodic, the output is also periodic. For signal processing, the binary states of 0 and 1 of the sequence have to be mapped into ± 1 by changing 1 to -1 and 0 to $+1$. Only the signs $+$ and $-$ are used for ± 1 in the figure and subsequent discussions.

If S_o is sampled at the clock frequency of the sequence, one has in matrix form the following relationship for the cross-correlation:

$$[h] = 7^{-1}[M_7][S_o] \quad (1)$$

where $[M_7]$ is a 7×7 matrix containing the right circularly delayed version of the sequence $M(\cdot)$ with a period equal to seven times the clock period. For this special case, the number of stages, m , used in the shift-register arrangement is 3. Since the elements of $[M_7]$ are all ± 1 , only additions and subtractions are required to perform the matrix multiplication $[M_7][S_o]$.

MATRIX MULTIPLICATION VIA FAST HADAMARD TRANSFORM

The computation of $[M_7][S_o]$ can be performed efficiently by using special techniques developed in Hadamard spectroscopy. These techniques involve

finding the permutation equivalence $[M] = [P][H][Q]$ between the m -sequence matrix M and the Sylvester-type Hadamard matrix H such that the fast Hadamard transform can be applied to obtain $[M_7][S_0]$. Specific procedures for constructing the permutation matrices P and Q can be found in earlier work,^{3,11,12} but the one presented by Cohn and Lempel¹³ is the easiest to follow and will be discussed in the following sections by using the example of Fig. 2.

Fast Hadamard transform

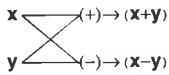
Analogous to the fast Fourier transform, the fast Hadamard transform is an efficient algorithm for performing a Sylvester-type Hadamard-matrix multiplication. The elements of a Hadamard matrix are all ± 1 . An account on the construction of these matrices of orders 1, 2, 4, 8, 16, ..., 2^m can be found in a book by Harwit and Sloane.¹² For example, a Sylvester-type Hadamard matrix of order 8 has the following form:

$$[H_8] = \begin{bmatrix} + & + & + & + & + & + & + & + \\ + & - & + & - & + & - & + & - \\ + & + & - & - & + & + & - & - \\ + & - & - & + & + & - & - & + \\ + & + & + & + & - & - & - & - \\ + & - & + & - & - & + & - & + \\ + & + & - & - & - & - & + & + \\ + & - & - & + & - & + & + & - \end{bmatrix} \quad (2)$$

and a direct evaluation of the following matrix multiplication

$$\begin{bmatrix} + & + & + & + & + & + & + & + \\ + & - & + & - & + & - & + & - \\ + & + & - & - & + & + & - & - \\ + & - & - & + & + & - & - & + \\ + & + & + & + & - & - & - & - \\ + & - & + & - & - & + & - & + \\ + & + & - & - & - & - & + & + \\ + & - & - & + & - & + & + & - \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \end{bmatrix} = \begin{bmatrix} (+a+b+c+d+e+f+g+h) \\ (+a-b+c-d+e-f+g-h) \\ (+a+b-c-d+e+f-g-h) \\ (+a-b-c+d+e-f-g+h) \\ (+a+b+c+d-e-f-g-h) \\ (+a-b+c-d-e+f-g+h) \\ (+a+b-c-d-e-f+g+h) \\ (+a-b-c+d-e+f+g-h) \end{bmatrix} \quad (3)$$

will require 56 operations. The fast Hadamard transform does this in three steps, since m equals three for the above Hadamard matrix of order 8. The procedure can simply be expressed by the flow graph shown in Fig. 3 adapted from the work of Borish and Angell.¹¹ The total number of



Basic Butterfly Element

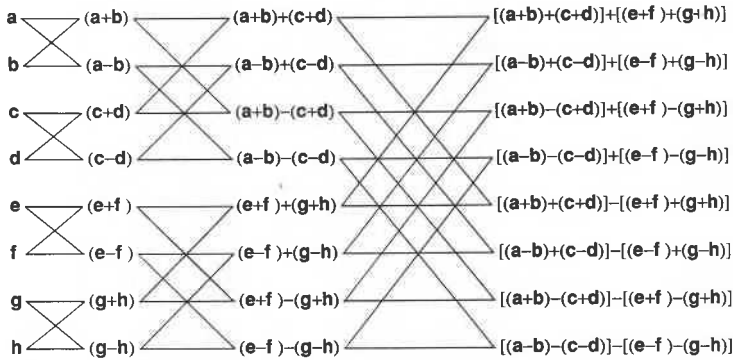


Fig. 3. Flow graph for an eight-point fast Hadamard transform.

operations for this case is only 24. In general, the fast Hadamard transform requires $L(\log_2 L)$ instead of $L(L-1)$ operations.¹² A Fortran code for this transform is given by Ando.⁵

Permutations

Except for the extra first row and first column, the matrix H_8 of eqn (2) is similar to the matrix M_7 of Fig. 2. The essence of the current technique is that, by adding a row and a column of $+1$ to the matrix M_7 , one can reorder the rows and columns of the augmented matrix to transform it into $[H_8]$.

Using the binary representation (i.e. 0 and 1 instead of ± 1) and modulo-2 arithmetic, Cohn and Lempel¹³ have shown that any m -sequence matrix M (of dimension $n \times n$) can be factored into two matrices: a matrix R (of dimension $n \times m$) and a matrix C (of dimension $m \times n$) where $[C]$ is formed by the first m rows of $[M]$. The matrix R is chosen from the columns of $[M]$ such that the first m rows of $[R]$ form an $m \times m$ unit matrix. An example based on the matrix M_7 of Fig. 2 is shown in Fig. 4.

Similarly, the Sylvester-type Hadamard matrix H (of dimension $L \times L$) can also be factored into two matrices: a matrix B (of dimension $L \times m$) and a matrix B^T (of dimension $m \times L$) where B^T is the transpose of B . The i th row of $[B]$ is the m -bit base-2 representation of the integer i , $i = 0, 1, \dots, L-1$. An example of the matrix H_8 is also shown in Fig. 4. If the rows of $[R]$ and the columns of $[C]$ are tagged according to the integer equivalence of their m -bit digits as shown in Fig. 4, it is obvious that $[M_7]$ and $[H_8]$ contain the same elements in a different order. Note that the tags of the rows and columns of

Modulo-2 Arithmetic:

+	0	1
0	0	1
1	1	0

$$\begin{aligned}
 [M_7] &= \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} \begin{matrix} 4 \\ 2 \\ 1 \\ 6 \\ 3 \\ 7 \\ 5 \end{matrix} \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \end{bmatrix} \\
 &\quad [R] \qquad \qquad [C]
 \end{aligned}$$

$$\begin{aligned}
 [H_8] &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{matrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{matrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \\
 &\quad [B] \qquad \qquad [B^T]
 \end{aligned}$$

Fig. 4. Factorization of the m -sequence matrix and the Sylvester-type Hadamard matrix. Beside each factored matrix are the corresponding 'tags' for each row or column.

the matrices B and B^T are always in ascending numerical order. Thus, using the tags of $[R]$ and $[C]$, one can transform $[M_7]$ into $[H_8]$ in three steps.

- (1) Use the tags of $[C]$ to reorder the columns of $[M_7]$ of Fig. 2 (i.e. move the seventh column of $[M_7]$ (whose tag = 1) into the first-column position, and the sixth column (whose tag = 2) into the second-column position, etc.) to form the permuted matrix M'_7 , where

$$[M'_7] = \begin{bmatrix} + & + & + & - & - & - & - \\ + & - & - & + & + & - & - \\ - & + & - & + & - & + & - \\ + & - & - & - & - & + & + \\ - & - & + & + & - & - & + \\ - & - & + & - & + & + & - \\ - & + & - & - & + & - & + \end{bmatrix} \quad (4)$$

- (2) Use the tags of $[R]$ to reorder the rows of $[M'_7]$ (i.e. move the third row of $[M'_7]$ (whose tag = 1) into the first-row position, the second row (whose tag = 2) into the second-row position, and the fifth row (whose tag = 3) into the third-row position, etc.).
- (3) Add a row and a column of + to the last matrix to transform it into $[H_8]$.

OUTLINE OF THE CROSS-CORRELATION PROCESS

Having established the transformation between $[M_7]$ and $[H_8]$, one can formulate the following procedure to compute $[h]$ by using $[H_8]$ instead of $[M_7]$.

- (1) Generate the matrix M from one period of the m -sequence.
- (2) Factor $[M]$ into $[R]$ and $[C]$ (Fig. 4).
- (3) Obtain the row tags of $[R]$ and the column tags of $[C]$ according to the integer equivalence of their m -bit binary digits. If a triggerable m -sequence generator is used, the permutation tags can be generated once and stored for all subsequent experiments by using the same sequence.
- (4) Reorder the elements of $[S_o]$ by using the column tags of $[C]$ and add a zero element to the permuted column matrix S'_o to form $[S''_o]$ (Fig. 5).
- (5) Apply the fast Hadamard transform to $[S''_o]$ to give $[h'']$ (Fig. 5).
- (6) Omit the first element of $[h'']$ and reorder the elements of the resulting matrix, h' , by using the row tags of $[R]$ given in Fig. 4 to give the impulse response $[h]$. However, the reordering process will be reversed. Here, one takes the fourth element of $[h']$ as the first element, the second element of $[h']$ as the second element, and the first element of $[h']$ as the third element, etc.

$$\begin{bmatrix} + & + & + & + & + & + & + \\ + & - & + & - & + & - & + \\ + & + & - & - & + & + & - \\ + & - & - & + & + & - & + \\ + & + & + & + & - & - & - \\ + & - & + & - & - & + & - \\ + & + & - & - & - & + & + \\ + & - & - & + & - & + & - \end{bmatrix} \begin{bmatrix} 0 \\ S_7 \\ S_6 \\ S_4 \\ S_1 \\ S_5 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} (+S_7+S_6+S_4+S_1+S_5+S_2+S_3) \\ (-S_7+S_6-S_4+S_1-S_5+S_2-S_3) \\ (+S_7-S_6-S_4+S_1+S_5-S_2-S_3) \\ (-S_7-S_6+S_4+S_1-S_5-S_2+S_3) \\ (+S_7+S_6+S_4-S_1-S_5-S_2-S_3) \\ (-S_7+S_6-S_4-S_1+S_5-S_2+S_3) \\ (+S_7-S_6-S_4-S_1-S_5+S_2+S_3) \\ (-S_7-S_6+S_4-S_1+S_5+S_2-S_3) \end{bmatrix}$$

$[H_8] \qquad [S''_o] \qquad [h'']$

Fig. 5. Illustration showing the product of the Hadamard matrix and the permuted matrix of the output signal.

The reader can easily verify the procedure by using the example given in Figs 2, 4, and 5.

REVERBERATION DECAY

According to Schroeder,¹⁴ the ensemble average $\langle s^2(t) \rangle$ of the squared decaying-sound pressure at a receiving point in a room excited by a white-noise signal is equal to a certain integral over the squared impulse response $h^2(\tau)$ of the room. Mathematically, the relation can be written as follows:

$$\langle S^2(t) \rangle = N \int_t^\infty h^2(\tau) d\tau \quad (5)$$

where N is proportional to the power-spectral density of the noise in the measured frequency range. For narrow-band applications, one can either use filtered white-noise excitation or perform a narrow-band filtering on the broad-band impulse response. Aoshima¹⁵ suggested another approach, involving the use of the Fourier transform of the impulse response. His method requires one Fourier transform for each data point in the decay curve. For reasonable resolutions in both the time and the frequency domains, this approach requires one to compute and store in computer memory at least fifty 10k-point transforms. This is beyond the capabilities of most microcomputers.

EXPERIMENTS

Some preliminary results for impulse-response and reverberation-decay measurements have been reported by the present author,⁸ using the cross-correlation technique based on a recipe given by Harwit and Sloane,¹² which was modified later according to the procedure given in the previous section. These results showed that the decay curve obtained by the present method compared well with the curves determined by the traditional method.

Additional experiments have been performed to demonstrate that impulse-response and reverberation-decay measurements can be obtained in very noisy environments. These measurements were taken for one fixed microphone and source position in a model reverberation chamber with dimensions 3.2 m \times 2.6 m \times 1.96 m. The chamber was equipped with fixed diffusers only. High-level non-stationary background music was deliberately introduced into the room by using a radio. For this series of experiments, an IBM AT-compatible microcomputer was used together with an A/D board (MicroWay A2D-160), which has a built-in m -sequence generator and a software package written in assembly language that can perform the impulse-response calculation efficiently.

For impulse-response and reverberation-decay measurements, the period of the m -sequence should be at least as long as the reverberation time to cover a 60-dB decay range. Thus, a sequence of length $n = 2^{16} - 1 = 65\,535$, operating at a clock frequency of 20 kHz, was used for our experiments. The test signal was fed into a power amplifier and radiated into the room through a loudspeaker. The acoustical signal at one chosen location in the room was measured with a 25.4-mm B&K microphone, whose output was sampled at the same clock frequency of 20 kHz. The microphone signal was averaged over a predetermined number of periods to enhance the signal-to-noise ratio before the impulse-response and the decay curve were computed.

RESULTS AND DISCUSSIONS

Figure 6(a) shows the measured broad-band impulse response for the chosen microphone and source position with no background music. The signal used was at least 50 dB above the ambient background noise. Five averages were used to reduce the influence of this ambient background noise in the room to establish base-line results for comparisons. The impulse response was normalized by its maximum value. A similar broad-band impulse response measured in a simulated noisy environment by using music from a radio is presented in Fig. 6(b). The signal used was 9 dB below the background music. By using 100 averages for this case, the recovered impulse response compared well with that of Fig. 6(a) as indicated by the differences plotted in Fig. 6(c), whose axes of ordinates have been magnified ten times.

A comparison of the decay curves computed from these impulse responses by using eqn (5) is shown in Fig. 7. Agreement to within 1 dB was obtained for the initial 27-dB range of decay. Better dynamic range can be obtained if more averages are used. In general, one can expect a gain in signal-to-noise ratio of $10 \log_{10} N$, N being the number of averages used. However, this gain will not be fully reflected in the dynamic range of the decay curve because of the accumulative effect inherent in the summation process of eqn (5). More detailed investigation is required to establish criteria for choosing the appropriate number of averages to achieve a certain dynamic range of the decay curves. The number of averages required will depend on the length of the m -sequence used, the characteristics of the background noise present, and the band-width of the analysis.

To show that the current method is also applicable for narrow-band analyses, the impulse response of Fig. 6b was digitally filtered by using a 6-pole Butterworth digital filter whose response satisfies the requirements of ANSI S1.11-1966 class II for a 2-kHz octave-band filter. A comparison of its

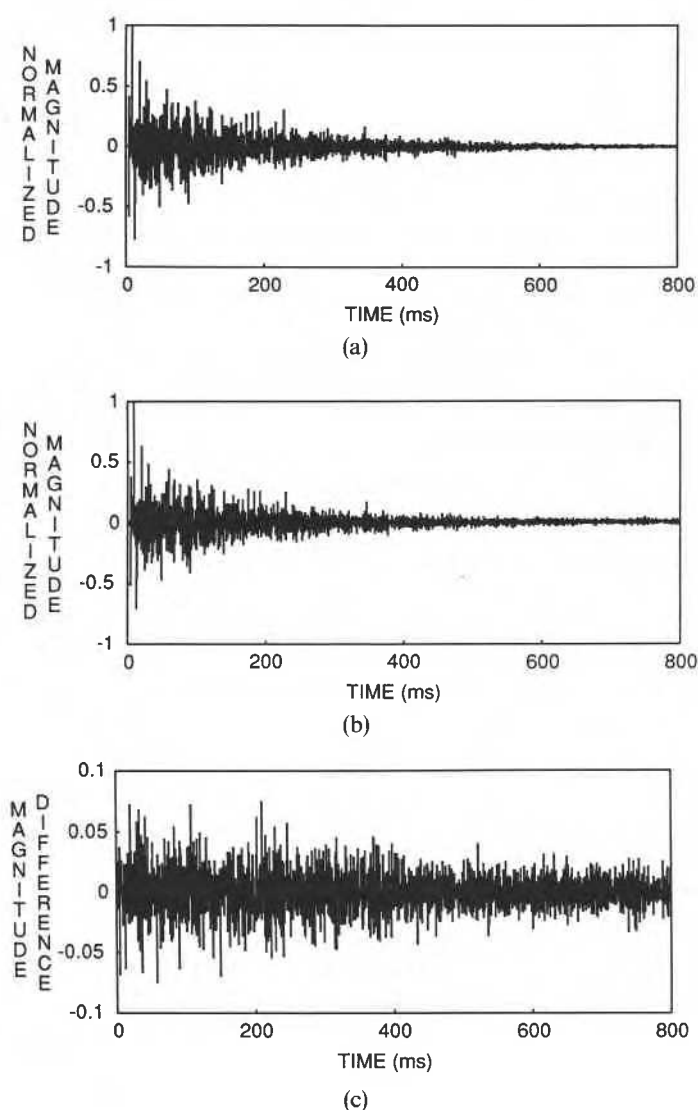


Fig. 6. Comparison of the broad-band impulse responses measured with different signal-to-noise ratio: (a) with no background music and signal more than 50 dB above background; (b) with background music and signal 9 dB below background (100 averages); (c) difference between the two impulse responses of (a) and (b).

filter characteristic with that of a Bruel & Kjaer type 1613 analog octave filter is shown in Fig. 8, and the computed decay curve is shown in Fig. 9. For comparison, a decay curve obtained by exciting the room with a filtered *m*-sequence signal and using the Bruel & Kjaer analog octave-band filter is also depicted in Fig. 9. No background music was introduced in this

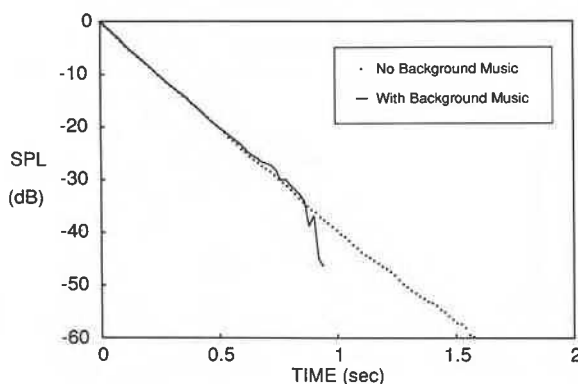


Fig. 7. Comparison of the broad-band decay curves computed from the impulse responses of Fig. 6.

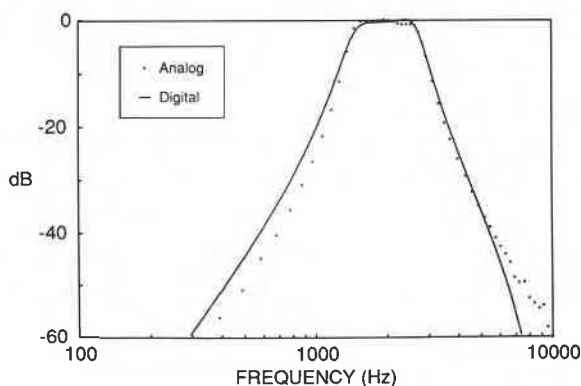


Fig. 8. Comparison of the filter characteristics of the six-pole Butterworth digital-octave filter and the Bruel & Kjaer Type 1613 2-kHz analog octave filter.

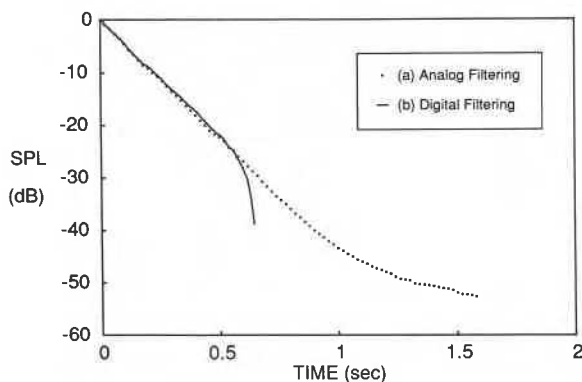


Fig. 9. Comparison of the 2-kHz octave-band decay curves: (a) from the impulse response obtained by exciting the room with analog-filtered *m*-sequence signal and no background music; (b) from digitally filtering the broad-band impulse response of Fig. 6(b).

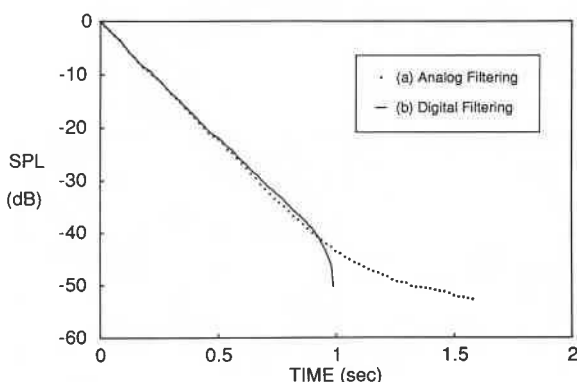


Fig. 10. Comparison of the 2-kHz octave-band decay curves: (a) from the impulse response obtained by exciting the room with analog-filtered *m*-sequence signal and no background music; (b) from digitally filtering the broad-band impulse response of Fig. 6(a).

measurement. Agreement to within 1 dB was obtained for the initial 24-dB range of decay.

Better dynamic range for the case with digital filtering can be expected if a broad-band impulse-response curve with less contamination of background noise is used as input. This is shown by a similar comparison in Fig. 10 with the impulse-response curve of Fig. 6a used as the input. The agreement of the decay curves is fairly good (within 1 dB for the initial 30-dB range of decay), which indicates that narrow-band results can be obtained from the broad-band impulse response by using digital filtering.

CONCLUSION

A fairly detailed account of the cross-correlation method involving the use of a periodic pseudorandom sequence for impulse-response and reverberation-decay measurements has been given. Experimental results are also provided to demonstrate its potential for making measurements in very noisy environments. Good signal-to-noise ratio can be obtained because of the immunity of the cross-correlation method to unrelated background noise and the possibility of using long sequences and averaging. The existence of an efficient algorithm based on the fast Hadamard transform for performing the cross-correlation has made this method a very powerful measuring technique. At $t = 0$, eqn (5) gives the mean-square pressure. Thus, the current method can also be used for attenuation or transmission-loss measurements.

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