

Limitations in using Golay codes for head-related transfer function measurement

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Although the use of Golay codes has been recommended for measuring external-ear impulse responses [Zhou *et al.*, *J. Acoust. Soc. Am.* **92**, 1169–1171 (1992)], this report demonstrates a potential limitation that could arise in applications requiring probe stimulus excitation to last longer than a few hundreds of milliseconds. In such situations, artifacts in the measured impulse responses can result from using Golay codes if the system under evaluation is time variant. These impulse-response artifacts are demonstrated for measurements of human binaural impulse responses (equivalent to head-related transfer functions, or HRTFs) under conditions analogous to small head movements during the measurement procedure. A popular alternative impulse-response measurement technique using maximum-length sequences (MLSs) does not produce artifact-contaminated measurements under the same conditions. © 2000 Acoustical Society of America. [S0001-4966(00)03303-8]

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INTRODUCTION

Modern signal-processing techniques have afforded researchers a variety of methods for measuring the impulse responses of linear time-invariant systems. Popular methods have included periodic pulse testing (Berman and Fincham, 1977), dual-channel fast fourier transform (FFT) analysis (Pope, 1998), time-delay spectrometry (Heyser, 1967), as well as various methods relying on excitation with types of deterministic noise signals. One particular type of deterministic noise signal that has been utilized for impulse-response measurement is the Golay code (Foster, 1986). Given both its superior signal-to-noise ratio when compared to measurements with conventional impulse-signal excitation, as well as its implementational ease, Golay codes have been specifically recommended for measuring human external-ear impulse responses (Zhou, Green, and Middlebrooks, 1992), or equivalently, head-related transfer functions (HRTFs).

External-ear impulse-response measurement using live humans presents a number of challenges to the measurement method employed. In addition to both efficiency and noise immunity requirements, the given measurement method must be able to handle mild violation of system time invariance, since humans are arguably always time-variant systems. Although all methods of impulse-response measurement will produce errors when the system under evaluation is not strictly time invariant, this report shows that the Golay method can produce particularly deleterious artifacts in the measured impulse response under these conditions. As such, users of the Golay method should be aware of these potential limitations.

Following a brief description of the Golay method, these artifacts will be demonstrated by binaural impulse-response

measurements made under the time-variant conditions of simulated head movement. Results are compared to measurements made with a popular alternative method of impulse-response measurement using a different deterministic noise signal known as the maximum-length sequence (MLS).

I. THE GOLAY TECHNIQUE

Golay codes, named after their creator, Marcel Golay (1961), are complementary pairs of radix two digital sequences that may be generated by a simple recursive relation (given in Golay, 1961; Foster, 1986; and Zhou, Green, and Middlebrooks, 1992). The codes have the noteworthy property that the sum of the autocorrelation functions for each code is only nonzero at zero lag. Figure 1 demonstrates this complementarity, which holds for circular as well as noncircular autocorrelation. Since complementary pairs of these noise-like codes produce a perfectly flat magnitude spectrum, they appear ideally suited for use as impulse-response measurement excitation signals. Additionally, the system's impulse response can be determined by cross-correlating the responses to each of the codes in the pair with the codes themselves and summing the results. This property avoids the sometimes unstable frequency-domain division operations required for deconvolution by certain other impulse-response measurement techniques (e.g., Wightman and Kistler, 1989). Also, since both codes and responses are radix two, the cross-correlation operations may be efficiently implemented by use of the FFT to multiply complex conjugates in the frequency domain (Zhou, Green, and Middlebrooks, 1992).

Although Zhou, Green, and Middlebrooks (1992) describe implementation of the Golay method with only a single code pair excitation period, additional gains in signal-to-noise ratio can be realized by presenting multiple code periods to the system and averaging the results coherently.

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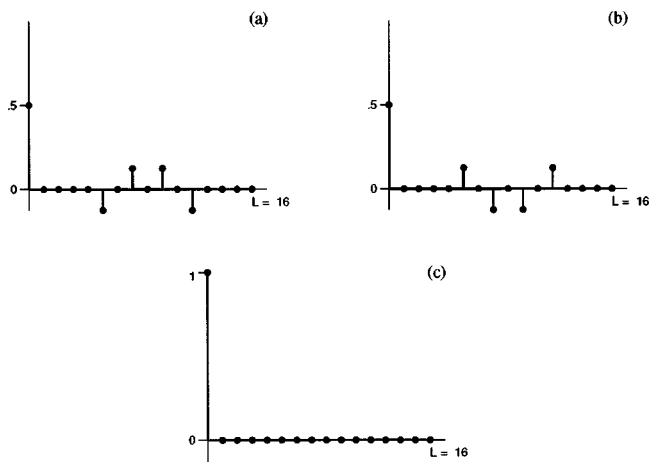


FIG. 1. Length $L=16$ Golay code circular autocorrelation functions for the individual complementary a and b codes, shown in panels (a) and (b), respectively, along with the sum of the individual autocorrelation functions, shown in panel (c). All functions have been normalized by $2L$.

Measurement of a system's (periodic) impulse response using this style of Golay code implementation proceeds as follows:

- (1) Generate a Golay code pair with length, L , sufficient to capture the system's expected impulse response, and avoid potential time-aliasing effects.
- (2) Excite the system periodically with k repetitions ($k \geq 2$) of the first (a) code in the Golay pair. Record and average the $k-p$ most recent results, where $k > p \geq 1$.
- (3) Wait for one code period.
- (4) Excite the system periodically with k repetitions of the second (b) code in the Golay pair. Record and average the $k-p$ most recent results.¹
- (5) Cross-correlate the response to the a code with the raw a code.
- (6) Cross-correlate the response to the b code with the raw b code.
- (7) Sum the results of 5 and 6 to arrive at the system's periodic impulse response.

For example, if the system being measured had a true impulse response that was a delta function, and this system were probed with a Golay code pair of length $L=16$, then the results of steps (5) through (7) may be represented by panels (a) through (c) of Fig. 1.

From this example, it may be seen that if the system being measured is time variant, then the Golay code responses are no longer complementary. Returning to this example, consider introducing additional gain into the system between a and b code probings. Panel (a) of Fig. 1 would look the same, but panel (b) would be scaled by an additional gain factor. The sum would therefore no longer have zeros at all nonzero lags. It would instead have a number of nonzero elements near lag $L/2$, which may all be considered artifacts caused by a time-variant system. Notice as well that if a small time delay were introduced into the system between a and b probings instead of a gain factor, similar nonzero elements near lag $L/2$ would result.

This complementarity violation may be of particular is-

sue when making impulse-response measurements on live human ears, since it is difficult in this circumstance to guarantee that the system being measured is time invariant. To the extent that live humans are unable to remain perfectly motionless during these measurements, and given that the HRTF is strongly dependent on head position, such systems are always time variant. With the Golay measurement technique, as the length of the codes and/or the number of averages taken become large, a longer period of time elapses between a and b code presentation. There is therefore a greater chance that the measurement participant is not in exactly the same position for both code presentations, and hence a greater chance of resulting artifacts in the measured impulse response.

Conversely, the possibility of system time variation due to head movement over the course of the measurement is much less likely with short measurement durations. The 20.48-ms total signal duration (no averaging) used by Zhou, Green, and Middlebrooks (1992) in making anechoic HRTF measurements, for example, made it very unlikely that measurements were contaminated by head movement. Noise level and time-aliasing constraints do not always allow for such short measurement durations in all applications, however. For instance, if HRTFs are to be measured in a reverberant room environment, longer codes are required to fully capture the room response and avoid time aliasing. Increased number of averages may also be required to increase signal-to-noise ratio in such applications.

II. A TIME-VARIANT SYSTEM TEST

To demonstrate these impulse-response artifacts, binaural impulse responses were measured from a single human participant under time-varying conditions simulating head movement. Measurements were made both using the Golay technique and a popular alternative technique based on maximum-length sequences (MLSs), a technique that has been described in detail by Rife and Vanderkooy (1989); Borish and Angell (1983); Schroeder (1975, 1979); and Nielsen (1998).

Briefly, MLSs are, like Golay codes, pseudorandom digital sequences with flat-magnitude spectra that are generated via recursion (binary shift registers). They are not, however, made up of two complementary sequences, but instead have only a single $2^n - 1$ length sequence that must be presented periodically to the system under evaluation. Like the Golay technique, impulse responses are computed in the MLS technique by cross-correlating (circular cross-correlation must be used in this case) the response to the MLS with the raw MLS.

A. Procedure

Binaural impulse responses were measured from a single individual (participant code: SNA) in an anechoic chamber using both Golay and MLS techniques. The sound source was a small loudspeaker (Cambridge SoundWorks Center/Surround IV) with a nominal position of 0° azimuth and 0°

elevation (directly in front of the participant) and 1.4 m in distance. Two conditions of system time variation analogous to that caused by head movements were examined. These conditions were produced by moving the loudspeaker clockwise along a circular arc (via a computer-controlled motor with movement accuracy of approximately 0.1°) either 5° or 10° in azimuth during the measurement process. Movements were initiated at the start of the measurement sequence with a rate chosen such that the desired movement angle would be traversed in the exact time allotted for measurement completion. Preliminary testing confirmed that this form of simulated head movement offered a substantial increase in movement precision and repeatability over actual participant head movement. The effect of noise produced by the are movement apparatus was also found to be minimal, at least -50 dB relative to the signal level. A third, time-invariant condition was also examined in which the loudspeaker remained stationary at 0° azimuth. Additional stationary measurements were made at 5° and 10° azimuth (left-handed coordinates), for purposes of comparison to the time-variant conditions.

Specifically developed software driving PC-controlled Tucker-Davis Technologies D/A and A/D hardware (model PD1) capable of real-time signal averaging was used to implement both Golay and MLS techniques. Binaural microphones (Sennheiser KE4-211-2) were used in a blocked canal (Møller *et al.*, 1995) fashion. For each of the measurement conditions, 100 averages of a 10th-order (1023 point) MLS and 100 averages of a 10th-order (1024 point) Golay code pair (50 contiguous-time averages for the *a* code followed by 50 contiguous-time averages for the *b* code) were obtained sampling at a rate of 50.0 kHz. The periodic stimulus excitation was initiated ten stimulus periods prior to data acquisition in all cases. These parameters yielded a total measurement duration of just over 2 s. The stimulus level at the position of the participant's head was approximately 75 dB SPL.

The participant was instructed to remain as motionless as possible during the duration of the measurements, although no explicit means to prevent movement were employed.

B. Results

Figure 2 displays the measurement results from the participant's left ear, with columns corresponding to measurement technique (Golay or MLS) and rows corresponding to movement angle (0° , 5° , or 10°). Little difference is observed between the two methods when the system is time invariant (0° of movement), other than a slight difference in gain most likely attributable to listener positioning differences in the two conditions. For the time-variant conditions (5° and 10° of movement), however, marked difference may be observed between the two methods, the Golay technique showing substantial artifacts in the time region between 10 and 20 ms. If the impulse-response maximum were shifted back to lag zero, removing the system's pure delay of approximately 4 ms, it can be seen that the Golay code artifacts present for the time-variant conditions do indeed exist about the region of lag $L/2$, which is approximately 10 ms in this case. Additionally, artifact amplitude appears to be positively related to

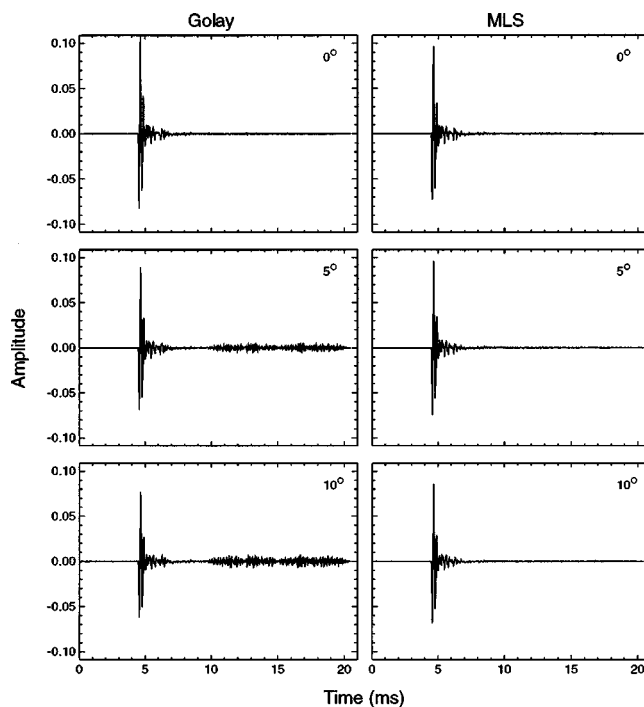


FIG. 2. Binaural impulse responses (left ear displayed) measured using Golay and MLS techniques under conditions of 0° , 5° , or 10° of loudspeaker movement during the measurement procedure.

movement magnitude. Results from the right-ear measurements are very similar to those displayed for the left ear in Fig. 2.

Note that the impulse responses measured in either of the time-variant cases are not expected to be the same as those measured in the time-invariant case. Both measurement techniques return an average response to source positions between either 0° and 5° , or 0° and 10° in these circumstances. This assertion may be verified by examination of Fig. 3, which displays the transfer functions from each of

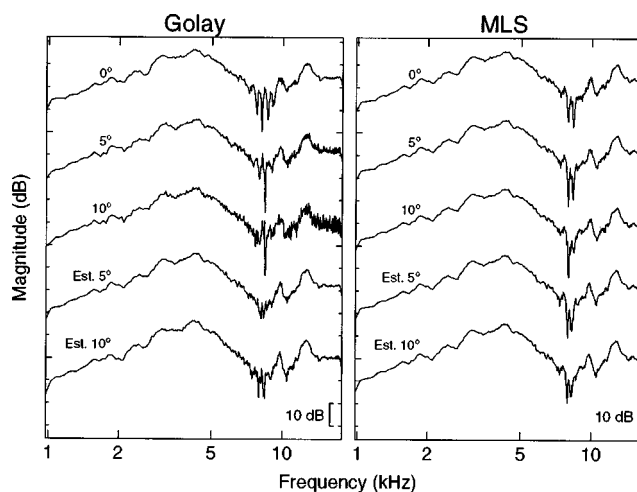


FIG. 3. Measured and estimated transfer functions using Golay and MLS techniques. The measured functions correspond to the impulse responses displayed in Fig. 2 under conditions of 0° , 5° , or 10° of movement. Estimates of the 5° and 10° functions are also displayed, based on the mean of log-magnitude spectra measured at static azimuth angles of 0° and 5° or 0° , 5° , and 10° , respectively. All functions have been displaced by increments of 30 dB for display purposes.

the three measurement conditions, along with estimated transfer functions for each of the movement conditions. These estimated functions are means of the log-magnitude spectra measured at stationary azimuth angles of 0° and 5°, or 0°, 5°, and 10°. For the MLS technique, the estimated functions are quite similar to the measured functions for both 5° and 10° of movement. This suggests that, in the time-variant cases, the MLS technique does not introduce any errors in addition to that of returning an average response to positions over the movement arc. For the Golay technique, however, less similarity exists between the estimated and measured movement condition functions, with the high-frequency noise in the measured functions being a result of the artifacts observed in the impulse responses measured using this technique.

While system time variance has been discussed primarily in terms of variation between successive presentations of the digital sequences, it should also be noted that time variation within the presentation of a single sequence can cause errors. For the MLS technique, Vanderkooy (1994) has shown that these errors are relatively trivial, manifesting themselves simply as uniform noise in the computed impulse response. The precise effect of this form of time variation of Golay codes is unknown, but is likely to be smaller than the between-pair time-variation effects demonstrated.

III. CONCLUSION

The Golay technique for impulse-response measurement has been shown to be susceptible to measurement artifacts caused by time-varying systems. As a result, caution is recommended in interpreting impulse responses measured with this technique if the systems under evaluation are known to be time varying, such as those involving nonstationary humans.

In practice, certain situations are more likely to result in contaminated measurements than others. When both noise level and time-aliasing constraints permit short measurement durations, such as the 20.48-ms duration used by Zhou, Green, and Middlebrooks (1992), these artifacts may be reduced to trivial levels. Likewise, strict control of system movement (e.g., by head immobilization) will undoubtedly reduce or eliminate time-variant artifacts as well. The additional practice of time-windowing measured impulse responses to remove room effects could also potentially remove most, if not all such artifacts. In situations where room effects are of interest, however, such as measuring binaural room impulse responses, the presence of these artifacts is not only much more problematic, but more probable as well. The increase in measurement time required to avoid time aliasing and achieve acceptable signal-to-noise ratios, in such situations, leads to a greater chance of system time variation over the course of the measurement. Not only are measurement artifacts of this type easily misinterpreted as room-response components, but they can also lead to significant errors in reverberant energy calculation.

The MLS technique has been shown to be more robust with respect to violations of system time invariance, and therefore may be considered preferable to the Golay technique for binaural impulse-response measurement applications where assumptions of system time invariance are questionable.

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¹Although not the averaging method suggested by Foster (1986), it is technically possible to present interleaved series of *a* and *b* code repetitions and average the results. To properly implement this method, a time period with no signal excitation must be inserted between *a* and *b* code presentations, however, in order to avoid capturing part of the response to the *a* code in the *b* code record, or vice versa. This scheme could, for example, take the form: [*a*₁, *a*₂, wait, *b*₁, *b*₂, wait, *a*₃, *a*₄, wait, ..., *b*_{*k*-1}, *b*_{*k*}]. The extra time periods with no signal excitation make this method less efficient than the suggested method of presenting and averaging all *a* code repetitions followed by all *b* code repetitions, [*a*₁, ..., *a*_{*k*}, wait, *b*₁, ..., *b*_{*k*}].

- Berman, J. M., and Fincham, L. R. (1977). "The application of digital techniques to the measurement of loudspeakers," *J. Audio Eng. Soc.* **25**, 370–384.
- Borish, J., and Angell, J. B. (1983). "An efficient algorithm for measuring the impulse response using pseudorandom noise," *J. Audio Eng. Soc.* **31**, 478–487.
- Foster, S. (1986). "Impulse response measurements using Golay codes," in *IEEE, 1986, Conference on Acoustics, Speech, and Signal Processing (ICASSP)* (IEEE, New York), Vol. 2 pp. 929–932.
- Golay, M. J. E. (1961). "Complementary series," *IRE Trans. Inf. Theory* **7**, 82–87.
- Heyser, R. C. (1967). "Acoustical measurements by time delay spectrometry," *J. Audio Eng. Soc.* **15**, 370.
- Møller, H., Sørensen, M. F., Hammershøj, D., and Jensen, C. B. (1995). "Head-related transfer functions of human subjects," *J. Audio Eng. Soc.* **43**, 300–321.
- Nielsen, J. L. (1998). "Improvement of signal-to-noise ratio in long-term MLS measurements with high-level nonstationary disturbances," *J. Audio Eng. Soc.* **45**, 1063–1066.
- Pope, J. (1998). "Analyzers," in *Handbook of Acoustics*, edited by M. J. Crocker (Wiley, New York), pp. 1341–1353.
- Rife, D. D., and Vanderkooy, J. (1989). "Transfer-function measurement with maximum-length sequences," *J. Audio Eng. Soc.* **37**, 419–444.
- Schroeder, M. R. (1975). "Diffuse sound reflection by maximum-length sequences," *J. Acoust. Soc. Am.* **57**, 149–150.
- Schroeder, M. R. (1979). "Integrated-impulse method measuring sound decay without impulses," *J. Acoust. Soc. Am.* **66**, 497–500.
- Vanderkooy, J. (1994). "Aspects of MLS measuring systems," *J. Audio Eng. Soc.* **42**, 219–231.
- Wightman, F. L., and Kistler, D. J. (1989). "Headphone simulation of free-field listening: I. Stimulus synthesis," *J. Acoust. Soc. Am.* **85**, 858–867.
- Zhou, B., Green, D. M., and Middlebrooks, J. C. (1992). "Characterization of external ear impulse responses using Golay codes," *J. Acoust. Soc. Am.* **92**, 1169–1171.