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Direct synthesis of pseudo-random ternary perturbation signals with harmonic multiples of two and three suppressed☆

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ABSTRACT

This paper proposes an analytical method to directly synthesise pseudo-random ternary perturbation signals for the identification of frequency response functions, through the multiplication of two components signals which satisfy a prescribed set of properties. The ternary signals generated have harmonic multiples of two and three suppressed; this specification is useful for reducing the effects of nonlinear distortion on the linear estimate. The signals have uniform magnitude in all, except two, of the nonzero harmonics. The method is significant in overcoming the existing problem of sparsity in the available periods when analytical methods are used, as well as the relatively long computational time required in approaches based on exhaustive search or computer optimisation. The proposed technique presents a breakthrough as it eliminates the sequence-to-signal conversion stage required in the existing conventional methods. A direct consequence is the increased signal power within amplitude constraints, which now equals the theoretical limit for the specification considered. If it is necessary to further increase the number of available periods, the mathematical derivation can be extended to a class of suboptimal direct synthesis signals; however, these possess reduced signal power compared with direct synthesis signals.
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1. Introduction

Perturbation signal design plays an important role in system identification. A well-designed signal enables sufficient amount of useful data to be gathered for the development of accurate process models. Periodic broadband signals constitute a favourable choice because they allow the avoidance of leakage effects, suppression of selected harmonics and reduction of the effects of noise through averaging (Pintelon & Schoukens, 2012). They are particularly useful if little prior information is available about the system under test. (If otherwise, optimal experiment design techniques (Müller, Rojas, & Goodwin, 2012; Wahlberg, Hjalmarsson, & Stoica, 2012) could be applied instead.) These signals can be classified into computer-optimised signals and pseudo-random signals (Godfrey, Tan, Barker, & Chong, 2005). In comparison with the former type of signals, the latter type possesses well-defined signal levels and power spectra but suffers from a lack of flexibility in terms of available periods.

In some instances, a system can only accept a limited number of input signal levels. In such cases, pseudo-random signals present a favourable option. Actuator limitation is a common cause; an example was given by Barker and Godfrey (1999) on a continuous hot-dip galvanising process for steel strip where a maximum of three levels could be applied. A similar point was made by Mohanty (2009), who applied ternary signals to excite a flotation column. Easier processing is another factor. Binary signals were utilised by Pinter and Fernando (2010) for the estimation of code division multiple access (CDMA) networks. Ternary signals were also applied in optical CDMA networks allowing a simple encoder to be used in the control base station (Yang, 2008). In Roinila, Helin, Vilkko, Suntio, and Koivisto (2009), the use of a pseudo-random binary signal allowed a simple circuitry to be implemented on a switched-mode converter. In Tan and Godfrey (2004), physical construction of the electronic nose system prevented the use of signals having more than four levels.

Harmonic suppression can be incorporated into the design of pseudo-random signals provided constraints relating to signal period and number of levels are satisfied. It can be utilised for detection of nonlinear distortion (Pintelon & Schoukens, 2012), elimination or reduction of effects of nonlinear distortion on the linear estimate (Evans & Rees, 2000) and in multivariable systems, making the input signals uncorrelated; the 'zippered' spectrum (Rivera, Lee, Mittelmann, & Braun, 2007) is an example of design of uncorrelated signals. Of particular interest is the suppression of harmonic multiples of two and three, which allows the effects of even order nonlinearities to be completely removed, and those of odd

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order ones to be reduced (Barker, Tan, & Godfrey, 2007). This necessitates the use of at least three signal levels. Unfortunately, the current existing designs for pseudo-random ternary signals, all of which are based on Galois fields (GFs), result in available periods which are rather sparse. Methods relying partially on exhaustive search or computer optimisation procedures have an additional drawback of relatively long signal generation time, compared with analytical methods. This may be of concern in applications such as signal generation in commercial spectrum analysers, where the user expects to obtain results almost instantaneously.

In this paper, a direct synthesis approach having a short generation time is proposed which significantly increases the available signal periods. The design presents a breakthrough as it allows the sequence-to-signal conversion stage in the creation of a maximum length signal from GF to be eliminated. In the existing designs, this stage leads to a loss in signal power due to the conversion of the zero field element. Additionally, the removal of this stage means that the signals can be created without prior knowledge of primitive polynomials associated with a particular GF.

The remainder of the paper is organised as follows. Section 2 provides an introduction to the problem at hand and an overview of the existing techniques. The proposed direct synthesis approach is introduced in Section 3. Section 4 offers a comparison between the proposed approach and the existing ones. The effectiveness of the proposed technique is illustrated in Section 5. Finally, concluding remarks are drawn in Section 6.

2. Signal generation in Galois fields

2.1. Problem statement and preliminaries

Consider a discrete ternary signal $u(i)$ having period N and discrete Fourier transform (DFT) denoted by $U(k) = \sum_{i=1}^{N} u(i) \exp\left(-\frac{2\pi jik}{N}\right)$.

Problem statement: find $u(i)\, \forall i \in \{m \mid 1 \le m \le N, m \in Z^+\}$ in order to maximise the root-mean-square (RMS) value of the signal

$$\mathrm{rms}(u) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} u^2(i)} \tag{1}$$

as well as the number of non-suppressed harmonics with uniform DFT magnitude represented by the cardinality of K, $\#K$, where $K = \{k \mid 0 \le k \le N-1, k \notin P \cup Q, |U(k)| = \max(|U(k)|)\}$, subject to

$$U(k) = 0 \quad \forall k \in P \cup Q, \quad \text{and} \tag{2}$$

$$u(i) \in \{1, 0, -1\}, \tag{3}$$

where $P = \{2m \mid 0 \le m < N/2, m \in Z\}$ and $Q = \{3m \mid 0 \le m < N/3, m \in Z\}$, with Z representing the set containing integers. Increasing $\mathrm{rms}(u)$ and $\#K$ would improve the signal-to-noise ratio (SNR) at the system output and the input magnitude uniformity at the excited frequencies, respectively. Theoretical limits dictate the following:

Constraint 1. $N \in \{6m \mid m \in Z^+\}$.

Proof. The condition $U(k) = 0\, \forall k \in P$ requires that

$$u(i) + u(i + N/2) = 0. \tag{4}$$

Furthermore, $U(k) = 0\, \forall k \in Q$ warrants that

$$u(i) + u(i + N/3) + u(i + 2N/3) = 0. \tag{5}$$

Combining (4) and (5) leads to Constraint 1.

Constraint 2. $\mathrm{rms}(u) \le \sqrt{2/3}$.

Proof. This follows from (3) and (5), since the maximum possible value of $\left(u^2(i) + u^2(i + N/3) + u^2(i + 2N/3)\right)$ is 2.

The sparsity in the signal manifested by the requirement given in (2) is used for the purpose of reducing the effects of nonlinear distortion on the linear estimate of the frequency response function. This is rather different from compressive sensing techniques (Baron, Sarvotham, & Baraniuk, 2010) which exploit sparsity to condense information in a compressible signal; this aims at reducing the required sampling rate. In particular, the requirement given in (2) ensures that all even order distortion terms will appear at even harmonics thus allowing them to be easily separated from the linear term at the system output. For example, since $U(k)$ can only be nonzero at $k \in \{1+6p, 5+6p \mid p \in Z\}$, second order terms can only occur at $1+6p+1+6q = 2+6z$, $1+6p+5+6q = 6z$ and $5+6p+5+6q = 4+6z$, where $q, z \in Z$. Similarly, third order terms can only fall at $1+6p+1+6q+1+6r = 3+6z$, $1+6p+1+6q+5+6r = 1+6z$, $1+6p+5+6q+5+6r = 5+6z$ and $5+6p+5+6q+5+6r = 3+6z$, where $r \in Z$. Since harmonic multiples of three are suppressed at the input, third order distortion terms can be effectively reduced by filtering out the terms $3+6z$ at the system output.

2.2. Maximum length signals from Galois fields

Current approaches generate such ternary signals from GF(q), where $q \in \{a^m \mid a \text{ prime}, m \in Z^+\}$ and $q - 1 \in \{6m \mid m \in Z^+\}$. A maximum length sequence $s_{q,n}(i)$ of order n and period $N = q^n - 1$ is acquired through a recurrence relation

$$s_{q,n}(i) = -\sum_{r=1}^{n} c_r s_{q,n}(i-r), \quad i \in \{1, 2, \ldots, N\}. \tag{6}$$

This requires knowledge of the corresponding primitive polynomial $f_n(x)$, where

$$f_n(x) = \sum_{r=0}^{n} c_r x^r, \qquad c_0 = 1, \qquad (-1)^n c_n = g. \tag{7}$$

In (7), g is a primitive element satisfying $\{g^\gamma \mid 0 \le \gamma \le q-2, \gamma \in Z\} = \{1, 2, \ldots, q-1\}$. To convert $s_{q,n}(i)$ to a maximum length signal $u_{q,n}(i)$, a sequence-to-signal conversion function ξ must be obtained. Let X and Y be non-empty sets such that $X = \{x \mid 0 \le x \le q-1\}$ and $Y = \{1, 0, -1\}$. Then $\xi : X \to Y$.

When $n = 1$, a primitive maximum length signal $s_{q,1}(i) = g^{i-1}$ is obtained. By setting $u_{q,1}(i)$ to meet the harmonic specification, ξ is defined through

$$\xi : s_{q,1}(i) \in X \to u_{q,1}(i) \in Y \quad \text{and} \quad \xi(0) = 0. \tag{8}$$

Note that ξ is surjective in order for $u_{q,1}(i)$ to be ternary. However, ξ is not injective. This leaves some room in the design for increasing $\mathrm{rms}(u_{q,n})$ by mapping as many elements of X as possible into the elements ± 1 of Y. Defining $l, m \in Z$, the frequency domain properties of $u_{q,1}(i)$ and $u_{q,n}(i)\, \forall n > 1$ at harmonic k, $0 \le k \le N-1$ are related through (Barker, 2004)

$$|U_{q,n}(k)| = \begin{cases} |U_{q,1}(0)|q^{n-1} & \forall k \in \{m(q^n-1)\} \\ |U_{q,1}(0)|q^{(n-2)/2} & \forall k \in \{l(q-1)\},\ k \notin \{m(q^n-1)\} \\ |U_{q,1}(k)|q^{(n-1)/2} & \forall k \notin \{l(q-1)\}. \end{cases} \tag{9}$$

2.3. Existing methods

The existing methods for the design of $u_{q,1}(i)$ can be classified as follows:

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