A Guide to the Design and Selection of Perturbation Signals

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***Abstract* — There are now many types of perturbation signal that can be used for system identification. These include signals with fixed power spectra, computer-optimized signals for which the user specifies the required harmonics, and hybrids of the two. With so many types now available, it is often difficult for the user to know how to select a signal that will be most appropriate for a particular application. In this paper, the authors provide a general guideline to this selection in a number of different experimental situations, giving the reasons for the particular selection.**

I. Introduction

Perturbation signal design plays an important role in system identification. A suitable signal allows as much information as possible to be gathered within a given timeframe. Several publications have considered the design of perturbation signals and extensive comparisons between

many now available, choosing an appropriate signal is not always an easy task. In this paper, the authors first review the 78(b)53351(i)0.

provided on signal selection for various identification single-output (SISO) systems and multi-input multi-output (M

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treated here.

several advantages over non-periodic signals. Firstly, in frequency domain analysis, they avoid the effects o leakage. Secondly, the frequency spectrum can be designed suppression. Thirdly, they allo averaged thus resulting in a highe

$$\text{PIPS} = \frac{200(u_{\text{rms}}^2 - u_{\text{mean}}^2)^{1/2}}{u_{\max} - u_{\min}}\,\% \qquad u \tag{1}$$

$_{\text{rms}}$, u_{mean}, $u_{\max}$ and $u_{\min}$ are, respectively, the root mean square, mean, maximum, and minimum values of the signal. PIPS measures signal power within amplitude constraints, and is independent of the signal mean and amplitude. Its value is 0% for a signal with the worst possible performance and 100% for a signal with the best possible performance for the estimation of linear dynamics,

$_{\max}$ and $u_{\min}$ have equal duration or number of occurrences.

II. Fixed Spectrum Signals

The signals have well-defined periods and values of

^{k} – 1, where k is a positive integer >0:

- Quadratic Residue Binary (QRB), $N = 4k - 1$ and prime;
- Hall Binary (HAB), $N = 4k^2 + 27$ and prime;
- Twin Prime Binary (TP and $(k + 2)$ prime.

For all of these, PIPS = (

Quadratic Residue Ternar near-binary signal, having

In most of the cases describe applied together with frequency

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Ai Hui Tan is with the Faculty of Engineering, Multimedia University, prime or a power of an odd prime [6]. The sequence-to-signal conversion is done in such a way that the resulting signal is ternary. The period $N = q^k - 1$, where k is a positive integer > 1, while the value of PIPS depends on the sequence-to-signal conversion. The signals are inverse-repeat, with even harmonics suppressed. If N is an integer multiple of 6, which is possible if $q = 6k_1+1$, where k_1 is an integer, the spectrum at harmonic multiples of 2 and 3 can be made zero, while if N is an integer multiple of 30, which is possible if $q = 30k_1+1$, where k_1 is an integer, the spectrum at harmonic multiples of 2, 3, and 5 can be made zero. The spectrum at the nonzero harmonics can be made uniform by proper choice of sequence-to-signal conversion.

Pseudo-random multilevel (PRML) signals can also be obtained from GF(q), where q is prime or a power of a prime [6], but with different sequence-to-signal conversions; the value of PIPS depends on the conversion. As with MLT signals, the period $N = q^k - 1$, where k is a positive integer >1. Multiples of a particular harmonic can be made zero provided N is an integer multiple of that harmonic.

D. *Truncated MLT Signals [7], [8], [9]*

A particular choice of sequence-to-signal conversion proposed in [7] allows *truncated* MLT signals to be derived that have uniform spectrum at odd harmonics and zero at even harmonics. These signals are mapped using

$$m(i) = (-1)^{i-1}\,,\ i = 1, 2, \ldots, q-1 \tag{2}$$

where $m(i)$ is the primitive signal [10]. This design gives very large values of PIPS. The signal has a spectrum that is uniform at the odd harmonics and zero at the even harmonics. Further, the squared version of the signal has the spectrum uniform at even harmonics and zero at odd harmonics [8], which is useful in certain applications with nonlinear distortion (see Section V(B)). For this design, $N = \dfrac{2(q^k - 1)}{q-1}$ and $\mathrm{PIPS} = 100\left(q^{k-1} \times \dfrac{q-1}{q^k - 1}\right)^{1/2}\%$, where k is a positive integer > 1.

For $q = 6k_1 + 1$, another choice of sequence-to-signal conversion results in truncated MLT signals with harmonic multiples of 2 and 3 equal to zero and the remaining harmonics uniform. This uses

$$m_q(i) = [m_7 \quad m_7 \quad \ldots \quad m_7]\,,\ i = 1, 2, \ldots, q-1\,; \tag{3}$$

where $m_q(i)$ is the primitive signal generated from GF(q) and

$$m_7 = [+1 \quad +1 \quad 0 \quad -1 \quad -1 \quad 0]\,. \tag{4}$$

The spectrum of m_7 has harmonic multiples of 2 and 3 suppressed, and m_7 is repeated $(q - 1)/6$ times in a period of $m_q(i)$ [9]. At present, this is the only analytical method available for generating ternary signals with such a spectrum, where there is no upper limit for the signal period. For this design, $N = \dfrac{6(q^k - 1)}{q-1}$ and $\mathrm{PIPS} = 100\left(\dfrac{2}{3} q^{k-1} \times \dfrac{q-1}{q^k - 1}\right)^{1/2}\%$, where k is a positive integer > 1.

The idea of allowing multiple periods within a common period has recently been extended further [11], in which sets of *uncorrelated* signals obtained by computer search for values of q in the range from 5 to 31 are listed. The uncorrelated property in the time domain means that the nonzero values of the spectrum of each signal in the set occur at different harmonics. This proves very useful for the identification of multi-input systems (see Section VI(A)). As an example, the first half of the discrete Fourier transform (DFT) magnitudes of a set of five such signals obtained for $q = 13$ and $k = 2$ (common period = 168) is shown in Fig. 1.

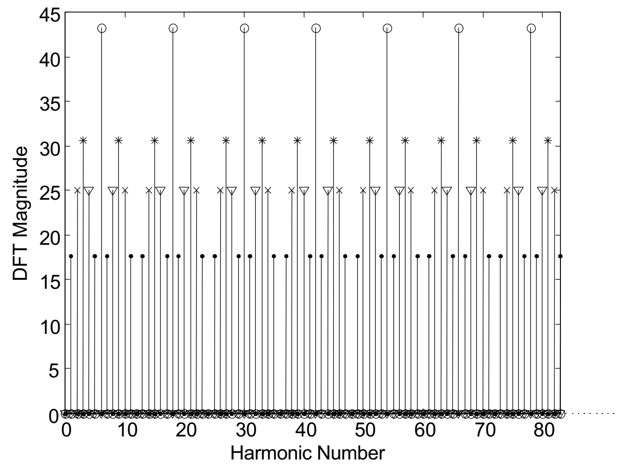

Fig. 1. First half period of the DFT magnitudes of a set of five uncorrelated signals from GF(13), with $k = 2$ [11]. The primitive signals are B (dots), E (crosses), F (asterisks), G (triangles) and H (circles).

The periods of the five signals in the set (these signals are named using letters following Table I in [11]) and their PIPS values are:

- Signal B: $N = 168$; PIPS = 81.65%;
- Signal E: $N = 84$; PIPS = 81.65%;
- Signal F: $N = 56$; PIPS = 100%;
- Signal G: $N = 42$; PIPS = 81.65%;
- Signal H: $N = 26$; PIPS = 100%.

III. COMPUTER-OPTIMIZED SIGNALS

There are four types of signal in this class. All of them have flexible periods limited only by the constraint that the period must be an integer multiple of any harmonic whose multiples are to be suppressed. They do not have a fixed PIPS value. Non-uniform spectra (for example logarithmic, band-pass) can be specified, but only multisine (sum of harmonics) signals can meet a user-defined specification exactly.

A. *Discrete Interval Binary (DIB) and Discrete Interval Ternary (DIT) Signals [12]*

For both of these types of signal, the objective of the optimization, usually based on the algorithm in [13], is to force as much power as possible into the specified harmonics. They can be designed with either the spectrum at all harmonics specified or with the spectrum at odd harmonics specified and that at even harmonics zero; in the latter case N must be even. DIT signals are often designed with the spectrum at harmonic multiples of 2 and 3 equal to zero, in which case N must be an integer multiple of 6.

B. Multilevel Multiharmonic (MLMH) Signals [14], [15]

The number of levels in this type of signal is finite and user-defined and the objective of the optimization is to adjust the relative phases of the harmonics, in order to minimize the crest factor (which in turn maximizes the value of PIPS), following the algorithm in [16]. MLMH signals with 2 or 3 levels can be used as alternatives to DIB and DIT signals, respectively. The possible harmonic specifications (and the consequent restrictions on N) are the same as for DIB and DIT signals.

C. Multisine (Sum of Harmonics) Signals [12]

The number of levels in this type of signal is not user-defined. The objective of the optimization is often to adjust the relative phases of the harmonics, in order to minimize the crest factor (which in turn maximizes the value of PIPS), following the algorithm in [16]. For some applications in nonlinear system identification, an amplitude distribution more closely resembling a Gaussian distribution is desired.

Almost any harmonic specification is possible, although suppressing the spectrum at harmonics that are multiples of an integer requires specific values of N. As with other types of computer-optimized signal, they can be designed with the spectrum at all harmonics specified or with the spectrum at odd harmonics specified and that at even harmonics zero; in the latter case N must be even. They are often designed with the spectrum at harmonic multiples of 2 and 3 equal to zero, in which case N must be an integer multiple of 6.

IV. Hybrid Signals

As far as the authors are aware, the only type of hybrid signal reported to date is Galois-multilev (Gallev) signals [17]. These are generated from GF(q) by first optimizing the primitive signal using the same algorithm as for MLMH signals, in order to obtain the required sequence-to-signal conversion. The sequence-to-signal conversion is then applied to obtain a Gallev signal from field q (with $k > 1$).

This method combines the deterministic nature of fixed spectrum signals and the flexibility of computer-optimized signals. The advantages are high PIPS values, short generation times, and a user-defined number of signal levels. However, nonzero harmonics are in most cases only close to uniform. Logarithmic and band-pass spectra are not possible.

V. Selection of Perturbation Signals For Single Input Systems

An important consideration in all applications is whether the input transducer is able to follow accurately a signal with many levels, such as a multisine, or whether it is necessary to restrict the number of levels to a small number. An example of this in practice was in the identification of the frequency response between the applied force and strip position of a scale model of a hot-dip galvanizing process for steel strip [18]. In this application, the electronics associated with the input transducer allowed movement of the strip by a given

Odd Order Nonlinearities

If the system has odd order nonlinearities (and possibly also even order ones), then the following types of signal are recommended:

Fixed Spectrum Signals – inverse-repeat MLB, truncated MLT signals with harmonic multiples of 2 and 3 suppressed;
Computer-optimized Signals – DIT (or 3-level MLMH) and multisine signals, with harmonic multiples of 2 and 3 suppressed;
Hybrid Signals – Gallev, with harmonic multiples of 2 and 3 suppressed.

For time domain identification, if the system has a Wiener structure, inverse-repeat MLB signals can be applied together with crosscorrelation analysis. The characteristic polynomial of the signal must be selected such that the significant peaks in the crosscorrelation function caused by odd order nonlinear terms are as far away as possible from the main linear peak. The positions of these peaks can be found using the software described in [5].

For frequency domain identification, the signal should have the spectrum at harmonic multiples of 2 and 3 suppressed, in order to reduce the effects of odd order nonlinearities. Thus, the signal must have at least 3 levels. To date, truncated MLT signals offer the highest possible PIPS values. However, they only exist for some values of $N = 6r$, where r is an integer. Gallev signals play an important role in filling up this gap. An application example was considered in [17] where the objective was to identify the linear dynamics of a Wiener system with odd and even order nonlinearities. A spectrum with 1000 uniform consecutive harmonics which are not multiples of 2 and 3 was specified. A Gallev signal from GF(79) with $N = 6240$ outperformed a ternary MLMH signal and an MLT signal in terms of PIPS value as well as the accuracy of the linear estimates obtained. The spectrum of the primitive signal of $N = 78$ used in the Gallev design is shown in Fig. 2.

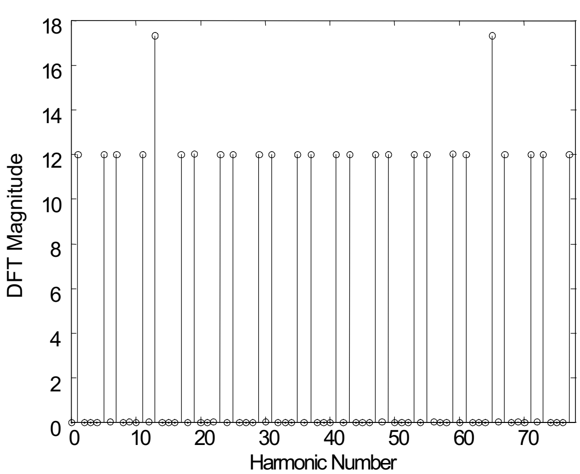

Fig. 2. DFT magnitude of primitive signal used in the Gallev design.

If a non-uniform spectrum or a log-scale harmonic specification is required, computer-optimized signals must be used.

C. For Estimating the Nonlinearity of a Nonlinear System

Wiener Systems

For the identification of the nonlinearity in such a system, many possibilities exist, and the choice of perturbation signal depends highly on the nature of the nonlinearity. In terms of signal power, binary signals provide that highest possible PIPS and can be applied to a system with a soft nonlinearity. However, for hard nonlinearities such as saturation, unless the amplitude and the sampling interval are chosen correctly, then the signal may not persistently excite the nonlinearity.

An example of such a situation is described in [20], where the nonlinearity was an ideal saturation function (hard clipping at $\pm$ 0.5). Using an inverse-repeat QRB signal with $N = 958$, it was found that the signal at the output of the linear dynamics (hence the input of the nonlinearity) was too large and did not equally span the input range of the nonlinear block. In fact, in this case, the linear dynamics term could not be estimated accurately either, due to having too few data points lying in the linear portion of the static plot. A signal with a larger number of levels is then required. Generally, harmonic suppression is useful. In this example, these problems were overcome by use of either MLT signals with zero spectral components at harmonic multiples of 2, 3, or 5, and multisines with various harmonic specifications.

In the example just mentioned, it may seem surprising that harmonic suppression was used to suppress the effects of nonlinear distortion, even though an aim of the test is to identify this distortion. The reason is that the technique applied first estimates the linear dynamics; this information is subsequently used to estimate the nonlinearity. A more accurate estimate of the linear dynamics would thus lead to a more accurate estimate of the nonlinearity.

Hammerstein Systems

In this case, the following types of signal are recommended:

Fixed Spectrum Signals – PRML signals;
Computer-optimized Signals – MLMH and multisine signals;
Hybrid Signals – Gallev.

The signals must have more levels than the highest degree of nonlinearity in the system. Using time domain analysis, the nonlinearity can be estimated by solving a matrix equation involving the Vandermonde matrix [21]. It was found in [21] that there is little point in using more than the minimum allowable number of signal levels. An important advantage of PRML signals is that the sequence-to-signal mapping can be fixed by the user. For the identification of a Hammerstein system, minimizing the condition number of a submatrix of the Vandermonde matrix is more important than maximizing the value of PIPS.

MLMH and Gallev signals can be applied provided the number of signal levels is greater than the degree of the nonlinearity.

Multisine signals are also a possible choice. When applying such a signal, the method of iterative identification proposed in [22] can be used. This requires the multisine signal to have random phases.

D. For Estimating the Structure of a Nonlinear System

For the general characterization of structure using Volterra kernels, the following type of signal is recommended:
Computer-optimized Signals – multisine signals with No Interharmonic Distortion (NID) spectrum [23], [24].

These multisines are designed such that there is no interharmonic distortion at the estimation lines at the system output. The power at every estimation line is due to only one combination of the input harmonics (up to a certain order, above which the nonlinear distortions become negligible). From the shape of the Volterra kernel, it is possible to obtain an indication regarding the structure of the system, whether it is Wiener, Hammerstein or Wiener-Hammerstein. Identification of Wiener-Hammerstein systems using NID multisine signals was considered in [25]. This method has a significant advantage in that only a single experiment is needed. However, a disadvantage with NID multisines is that they have very long periods, due to their sparse spectra.

VI. Extension to MIMO Systems

A. For Estimating the Underlying Linear Dynamics of a Linear or Weakly Nonlinear System which is not Ill-conditioned

The following types of signal are recommended:
Fixed Spectrum Signals – uncorrelated PRB signals, uncorrelated ternary signals derived from pseudo-random MLT signals;
Computer-optimized Signals – uncorrelated multisines with standard "zippered" spectrum.

Uncorrelated signals should be used to ensure that the effects of different inputs can be decoupled at the system outputs. For the identification of two-input systems, a PRB signal applied to one input and its inverse-repeat version applied to the other input is an attractive choice, as the two signals do not possess common harmonics across a common signal period.

One method of signal design proposed for systems with more than two inputs, is to use a PRB signal at one input and this signal modulated by {+1, -1}, {+1, +1, -1, -1}, {+1, +1, +1, +1, -1, -1, -1, -1}, etc. at the other inputs [26], [27]. However, this approach has a problem in that the common period increases significantly with the number of inputs, and for p inputs, the common period is $(2^{p-1})N$, where N is the period of the (original) PRB signal. An alternative is to use uncorrelated ternary signals derived from MLT signals – see Section II(D). These offer the possibility of specifying a standard "zippered" spectrum without using common periods that are unnecessarily long [11].

Time domain signal processing can also be used, with the same signal at each input, but with phase-shifting between the inputs [27]; this can be applied to any type of signal. The effects of the different inputs are separated in the time domain using input-output crosscorrelation functions.

B. For Estimating the Best Linear Approximation of a Linear or Weakly Nonlinear System which is not Ill-conditioned

The following type of signal is recommended:
Computer-optimized Signals – orthogonal multisines.

In [28], [29], the use of orthogonal multisines was proposed for estimating the best linear approximation of a MIMO system; the best linear approximation consists of the underlying linear dynamics plus the bias caused by nonlinearities. (This is in contrast with the objective in Section VI(A) which is to suppress the effects of nonlinearities. Here, the effects of the bias to the frequency response function are to be measured instead.) Orthogonal multisines have the signal to each input modulated in a succession of blocks by the entries of a deterministic unitary (orthogonal) matrix such as a DFT matrix. Signals used for every input in the first experiment are shifted orthogonally for the subsequent experiments. For a system with p inputs, at least p different experiments are required. The frequency response function measurements yield in the limit exactly the same best linear approximation measured with Gaussian noise, but with lower variance.

C. For Estimating the Underlying Linear Dynamics and Eigenvalues of a Linear or Weakly Nonlinear System which is Ill-conditioned

For systems which are ill-conditioned, directionality of the system presents an additional constraint in the design of a suitable set of perturbation signals. The system has a high gain direction and a low gain direction which can be determined through singular value decomposition. It is well known that large amplitude correlated components are necessary if the low gain direction is to be sufficiently excited for accurate estimation of the smallest eigenvalue(s).

Different techniques have been proposed in the literature to increase the excitation of the low gain direction. One method is to use rotated inputs [30], [31], where some of the inputs are "rotated" at certain angles which are either assumed to be approximately known *a priori* or obtained by trial and error. In practice, any type of signal can be "rotated". However, it should be noted that a rotated binary signal would not remain binary after rotation. Since the harmonic spectrum is no longer uniform after rotation, subsequent time domain analysis would be useful.

Another technique uses low amplitude uncorrelated binary signals to identify the high gain direction and high amplitude correlated binary signals to identify the low gain direction [32]. The uncorrelated and correlated binary signals can be applied alternately, or simultaneously in an additive manner. The idea proposed in [32] can be applied in the frequency domain by using a modified "zippered" spectrum [33], [34]. This spectrum is easily achieved by means of multisine signals.

VII. Conclusion

In this paper, the design of various types of perturbation signal has been reviewed, and selection of signals for several cases has been considered. The paper is intended to provide useful guidance to an engineer faced with a typical problem of perturbation signal selection. In particular, different identification objectives may require the use of different types of signals. The list of signals and problems is by no means exhaustive, and only a general guideline can be provided, since constraints such as the number of allowable input levels, amplitude bounds and plant-friendliness measures may affect the choice of signal.

Useful websites for signal generation software:

- PRB and near-binary signals and their inverse-repeat versions (free software for design with $N = 50{,}000$): http://www.eng.warwick.ac.uk/eed/dsm/prs;
- MLT and PRML signals (free software for design with $q = 31$): http://www.eng.warwick.ac.uk/eed/dsm/galois;
- DIB, DIT and multisine signals (commercial software): http://elecwww.vub.ac.be/fdident;
- MLMH signals (free software): http://www.eng.warwick.ac.uk/eed/dsm/multilev_new.

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