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Identification of a multivariable nonlinear and time-varying mist reactor system

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ABSTRACT

This paper considers the identification of a multivariable nonlinear and time-varying mist reactor system which presents an important system in the industry for applications in cell culture. A systematic approach is formulated for characterizing the linear dynamics, nonlinear distortion, disturbing noise and time variation. The best time-invariant approximation is introduced as part of the methodology in the proposed approach. By incorporating significant nonlinear terms into the model, the main source of disturbance can be determined with greater confidence. The power at the different harmonics is further capitalized upon in deriving an indicator for the relative variance of the time-varying delay.

1. Introduction

System identification plays a very important role in the area of control. A good experiment design maximizes the amount of useful information that can be collected within a specified time frame. This information, when processed appropriately, eventually results in a system model, whether parametric or non-parametric. A more accurate model generally leads to improved controller performance as tighter control can be utilized. In recent years, model-based controllers (Darby & Nikolaou, 2014; Ellis, Durand, & Christofides, 2014; Forgione, Bombois, & Van den Hof, 2015) have become very popular and have been shown effective for many practical applications. Such controller clearly relies heavily on the availability of a high-quality model.

An important step towards achieving accurate identification is through careful design of the perturbation signals. Existing designs can be categorized based on the number of signal levels, the method of generation as well as the harmonic content. It is well-known that the suppression of harmonic multiples of two allows the effects of even order nonlinearities to be separated at the system output thus ensuring that they do not distort the linear estimates (Pintelon & Schoukens, 2012). Further suppression of harmonic multiples of three will help reduce the effects of odd order nonlinearities (Tan, Barker, & Godfrey, 2015). However, it is less well-recognized that harmonic suppression applied together with a systematic analysis of the output spectrum is able to provide ample insights into the system, for example, in terms of detecting and quantifying even and odd order nonlinearities, as well as distinguishing between the effects of noise and time variation. This information is very important for deciding on a suitable model of the system. However, not many research reported in the literature capitalizes on this. Examples are work by Lataire, Louarroudi and Pintelon (2012) and Pintelon, Louarroudi and Lataire (2013) which provided detailed frequency domain analysis of the output spectrum for single-input systems. It should be noted that these are all very recent developments. As far as the authors are aware, results for multi-input systems are currently not available; this is unfortunate as such systems are very common in the industry. Further to this, most of the experimental results reported for single-input systems are based on implementations on electronic circuits.

Motivated by the importance of being able to identify multi-input systems and the existing gap in the area between academia and industry, the objective of this paper is to propose a systematic approach for characterizing multi-input systems in terms of linear dynamics, nonlinear distortion, disturbing noise and time variation using simultaneous perturbation in a single experiment. The step-by-step methodology allows the contribution of the various terms to be identified and added into the system model one at a time. This is an important advantage as it provides the user with the flexibility to tune the model accuracy and complexity according to the application. The user can make informed decisions on whether to include nonlinear and time-varying terms based on their significance. A second advantage of the approach is that it requires only a single experiment which is time-saving, as the time needed for transient removal is reduced. In industrial systems, the reduction in experimentation time leads directly to cost saving as interruption on normal operations is minimized. This is made possible by careful design of the harmonic content of the

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perturbation signals.

The proposed approach incorporates two significant novelties within its methodology. The first is the introduction of the concept of best time-invariant approximation (BTIA) incorporating the linear and nonlinear components of the system. By incorporating the significant nonlinear terms, the model error can be reduced to a level acceptable to the user depending on the requirements of the application. This makes it easier to subsequently distinguish the main source of disturbance in the system. The second is the derivation of a relative delay variance indicator for multi-input systems. This is derived from the version which is applicable for single-input systems (Tan , Cham, & Godfrey, 2015). The indicator is able to cope with different channels having different delay characteristics. To the best of the authors' knowledge, no other delay variance indicator has been reported in the literature aside from that by Tan , Cham, and Godfrey (2015). Besides the two significant novelties mentioned above, it is worth highlighting that the frequency domain indicator for determining the main source of disturbance (Lataire , Louarroudi, & Pintelon, 2012) is also extended from the single-input case to the multi-input case.

The main contributions of the paper are as follows:

(i) Formulation of a systematic approach for characterizing the linear dynamics, nonlinear distortion, disturbing noise and time variation in multi-input systems using simultaneous perturbation in a single experiment.
(ii) Introduction of a novel concept of BTIA incorporating the linear and nonlinear components of the system.
(iii) Derivation of a relative delay variance indicator for multi-input systems.
(iv) Detailed implementation of the proposed approach on a multi-variable industrial-relevant mist reactor system.

The rest of the paper is organized as follows. A systematic approach to characterize the multi-input systems in terms of linear dynamics, nonlinear distortion, disturbing noise and time variation is proposed in Section 2. The BTIA and the relative delay variance indicator for multi-input systems are explained, together with details of their advantages and limitations. Section 3 presents an overview of the mist reactor which forms the system under test in this paper. In Section 4, the identification of the multivariable BTIA model of the mist reactor is explained. In Section 5, the identification of the disturbances is discussed and the proposed relative delay variance indicator for multi-input systems is applied to the experimental data. Concluding remarks are drawn in Section 6.

2. Systematic approach for characterization of various contributions

This Section first presents the methodology of the proposed systematic approach for characterizing the linear dynamics, nonlinear distortion, disturbing noise and time variation in multi-input systems using simultaneous perturbation in a single experiment. This is followed by expounding on two important novelties which form part of the methodology, namely, the BTIA and the relative delay variance indicator for multi-input systems.

2.1. Step-by-step methodology

The steps for characterizing the various contributions in a multi-input system with r inputs and s outputs are as follows:

Step 1: Perturb all the inputs u_j (j=1, 2, ..., r) of the system simultaneously using a set of signals of period N which are uncorrelated (and hence also orthogonal) with one another. It is strongly preferred to incorporate suppression of even harmonics in all the signals so that the effects of even order nonlinearities can be separated and completely eliminated at the system output (Pintelon & Schoukens, 2012). This ensures that they will not distort the estimation of the linear dynamics. Further suppression of harmonic multiples of three can also be considered for reducing the effects of odd order nonlinearities on the linear estimates. However, this will be at the expense of longer experimentation time. Collect P periods ($P\geq2$) of the output(s) y_i (i=1, 2, ..., s) at steady-state.

Step 2: Compute the N-point discrete Fourier transform (DFT) U_j and Y_i corresponding to u_j and y_i, respectively. Plot the measured frequency response functions (FRFs) defined by $G_{ij}(z^{-1}) = Y_i(z^{-1})/U_j(z^{-1})$ for all the individual steady-state periods (1, 2, ..., P) and the averaged period. This allows for a detection of variations between the individual steady-state periods as well as variations between these and the averaged period. Such variations may indicate the presence of time-varying components.

Step 3: Plot the ($N\times P$)-point DFT of the output to visually gauge the significance of the various contributions, noting that those from the linear and nonlinear terms are limited to harmonics which are integer multiples of P. If harmonic suppression has been incorporated in Step 1, some indication of the contributions of the nonlinear terms can be attained by analyzing the power falling at the lines $P\times$(non-excited harmonics).

Step 4: Identify the linear dynamics and nonlinear terms (if necessary) to obtain the BTIA. Refer to Section 2.2 for more details on the BTIA.

Step 5: Compute and plot the frequency domain indicator for determining the main source of disturbance in the system (Lataire , Louarroudi, & Pintelon, 2012). If the indicator is significantly greater than 1, noise is likely to be the main source of disturbance whereas if it is close to 1, slowly varying parameter changes are likely to be dominant. Additionally, if the FRF plots in Step 2 show different phase shift for different individual steady-state periods, the time variation is likely due to time-varying delay.

Step 6: If the result from Step 5 indicates that time-varying delay is the dominant source of disturbance, utilize the relative delay variance indicator for multi-input systems to check the change of the delay variance. Refer to Section 2.3 for more details.

According to the step-by-step methodology, the user gradually builds up the model by incorporating first the linear terms, then the nonlinear terms and finally the time-varying terms. This offers the possibility to decide whether the model is of sufficient accuracy for its intended use after the inclusion of each component. The fact that only a single experiment is required means that less time is spent waiting for transient effects to decay. This saves both time and cost. Besides, this would minimize differences in the experimental setting caused by uncontrolled changes in the environment if several different experiments were to be conducted. Furthermore, the need to run only one experiment simplifies operational issues typically encountered in the industry.

2.2. Concept of BTIA

The BTIA referred to in Step 4 of the proposed approach will now be introduced. The BTIA is defined as the best time-invariant system which minimizes the root-mean-square (RMS) values of the output errors subject to constraints in terms of the number of model parameters. The number of model parameters is decided by the user based on trade-off between model accuracy and complexity. The BTIA is different from the more standard best linear time-invariant approximation (BLTIA) (Lataire , Louarroudi, & Pintelon, 2012; Pintelon et al., 2013) such that the BTIA includes nonlinear terms which are considered significant. The reason for choosing the BTIA over the BLTIA is because by incorporating the significant nonlinear terms into the model, the model error can be reduced. This makes it easier to subsequently distinguish the main source of disturbance in the system