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Removal of transient disturbances from oscillating measurements using nearest neighbors imputation

Inês M. Cecílio [a,*], James R. Ottewill [b], Harald Fretheim [c], Nina F. Thornhill [a]

[a] Centre for Process System Engineering, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK
[b] ABB Corporate Research Center, ul. Starowiślna 13a, 31-038 Kraków, Poland
[c] ABB Oil, Gas and Petrochemicals, Ole Deviks Vei 10, 0666 Oslo, Norway

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ABSTRACT

Transient disturbances in process measurements compromise the accuracy of some methods for plant-wide oscillation analysis. This paper presents a method to remove such transients while maintaining the dynamic features of the original measurement. The method is based on a nearest neighbors imputation technique. It replaces the removed transient with an estimate which is based on the time series of the whole measurement. The method is demonstrated on experimental and industrial case studies. The results demonstrate the efficacy of the method and recommended parameters. Furthermore, inconsistency indices are proposed which facilitate the automation of the method.

1. Introduction

Detection and diagnosis of plant-wide oscillations has been an active topic of research in the process and control loop monitoring communities. Oscillatory disturbances are dynamic disturbances that persist over a time horizon. In the time domain, measurements affected by oscillatory disturbances show repeating patterns. Often, the repeating patterns have non-sinusoidal shapes and may repeat intermittently, as exemplified in figures later in this paper (Figs. 4 and 15). As a result, in the frequency domain these disturbances can be characterized by single or multiple spectral peaks, or broad-band features [1].

As discussed in review papers [1,2], the methods developed to analyze oscillating disturbances are data-driven, and most of them extract properties from the time series of a process measurement or from the relations between time series of different measurements. An example is the non-linearity of the time series of a measurement. The more non-linear the time series is, the closer the measurement should be to the root cause of a nonlinear oscillating disturbance [3,4]. Outside the analysis of plant-wide oscillations, Qin [5] has reviewed data-driven methods of process monitoring which use statistical data-based models, and Venkatasubramanian et al. [6–8] have surveyed the use of data-based, analytical, and qualitative models.

It has been reported in the literature that the accuracy of oscillation analysis methods can be affected by the presence of unrelated transient disturbances [9]. A transient disturbance is a particular class of deviations in the trend of a system variable, which is defined by being short-lasting and seldom repeated within the time horizon of analysis [10]. Fig. 1 shows examples of transient disturbances. These include spikes (Fig. 1a and b) and sags (Fig. 1c), after which the system variable often returns to its underlying trend, as well as the responses of the system to step changes (Fig. 1b), after which the time series follows a different trend.

Transient disturbances modify time and frequency properties of the time series on which some oscillation analysis methods rely. According to the valve stiction review book by Jelali and Scali [9], examples of methods affected by outliers, sharp abrupt changes, and step changes include the methods of bicoherence [3] and surrogate analysis [4].

It would thus be interesting to automatically detect transient disturbances in oscillating measurements, and to remove the transients without significantly altering the underlying dynamics of

* Corresponding author.
E-mail address: i.cecilio09@imperial.ac.uk (I.M. Cecílio).

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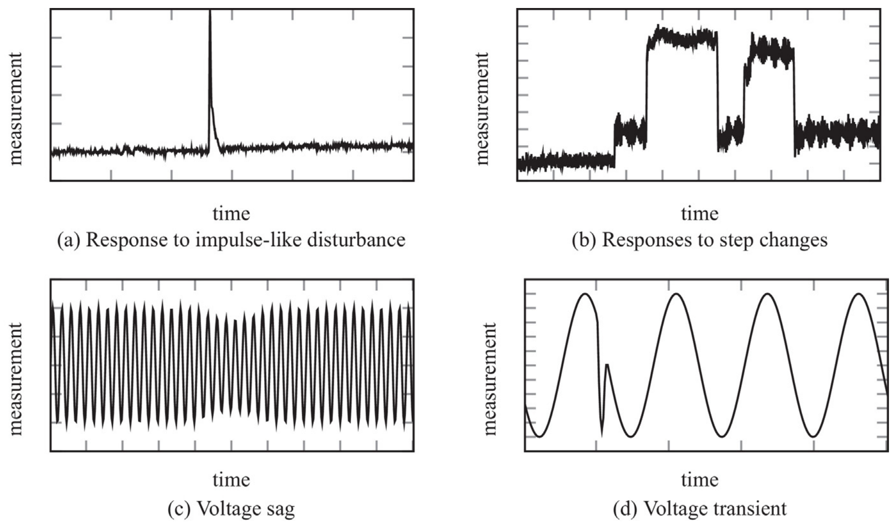

Fig. 1. Examples of transient disturbances.

the original measurements. As discussed below, important contributions have already been made to the *detection* of transient disturbances, but the *removal* of transients from oscillating measurements remains a challenge.

The *detection* of transient disturbances in process measurements has been addressed with Qualitative Trend Analysis (QTA), data-based models, wavelet decomposition, and nearest neighbors methods. Related work outside process and control loop monitoring includes the detection of edges in images [11], whereby edges are defined as step changes which can be masked by noise. QTA detects the transient disturbance by comparing its time trend with basic shapes [12]. As a result, QTA requires the creation of a complete database with all possible shapes of a transient disturbance. The traditional methods that use data-based models are known as statistical process monitoring, and assume that the time-domain magnitude of the transient disturbance is higher than the normal trend of the measurement [13]. As a result, statistical process monitoring methods would not recognize the transient disturbance in a measurement with oscillatory or cyclical dynamics if the transient had lower magnitude than the oscillations. Wavelet decomposition [14] is able to detect transient disturbances which map to wavelet coefficients in the lower scales, provided that the non-transient parts of the measurement do not produce other high-amplitude coefficients at those same scales. However, Cecílio et al. [15] showed an example of an oscillating measurement in which this condition was not met. The nearest neighbors method proposed by Cecílio et al. [10,15] is more generic than the previous approaches because it does not require the transient disturbance to have a specific shape, a higher magnitude or distinct wavelet coefficients. Instead, the method detects any rare and short-lasting deviation of a measurement from its previous and subsequent trend.

The *removal* of disturbance-related values from the time series of process measurements is often known as fault reconstruction [5]. The reconstructed values are estimates of what the time series would have been had the disturbance not been present. Existing methods require a statistical data-based model. This model reveals the relationships between the time series process measurements under normal operating conditions. Therefore, with such a model available, the reconstructed time series can be recalculated as linear combinations of all measurements available [16–18]. The data-based model most commonly derives from Principal Component Analysis (PCA) or Partial Least Squares (PLS) analysis of the matrix of process measurements [19,5]. Although in principle valid for any type of disturbance, the use of data-based models for removal of disturbances is limited to systems and types of operation for which accurate models have been built. Furthermore, this approach requires the knowledge of which measurements show the disturbance, and the existence of sensor redundancy [18].

Filtering in the frequency domain is a fundamental tool to isolate periodic oscillations in a measurement. This type of analysis determines the amplitude spectrum of the measurement, for example through Fast Fourier Transform, removes the range of undesired frequencies, and reconstructs the filtered time series. This approach, however, is not appropriate for removing transient disturbances because the frequency content of a transient is spread across the whole frequency spectrum. Also, this approach modifies the whole measurement, both in the removed frequencies and in the artifacts introduced by the filter, such as spectral leakage. These effects are not desirable when the objective is to carry out an oscillation analysis after the reconstruction.

The fields of image and speech processing have also devoted attention to decomposing a signal into oscillating components of different frequency contents [20]. However, as discussed, transient disturbances may not have a defined frequency range. Conversely, a more recent contribution [20] proposes a method to distinguish oscillating from transient components by the extent to which they are sustained, whereby *sustained* is defined as some number of consecutive oscillating cycles. However, as discussed at the start, oscillating disturbances in real process systems may repeat intermittently. Hence it could be ambiguous to judge whether the repeating patterns are sustained. Other works decompose the image or speech signal into linear combinations of orthonormal bases, formulating the decomposition as an optimization problem [21].

The method proposed in this paper removes transients from time series with oscillating disturbances. The method does not require the existence of models, and the time series is only modified locally, in the segment affected by the transient. The only requirement for the method is that the underlying trend of the time series has repetitive patterns, as exemplified in figures later in the paper (Figs. 4, 3 and 15).

The proposed method is based on a nearest neighbors imputation technique. This technique handles the measurement of a process variable as a time series, and replaces the removed transient disturbance with a segment of time series which agrees with the underlying trend of the original measurement. In other words,