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Isolating the source of whole-plant oscillations through bi-amplitude ratio analysis

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Abstract

Derived from bi-spectral analysis, a new diagnostic index, the bi-amplitude ratio, is proposed as an aid to the isolation of the source of non-linearity-induced oscillations that can propagate through a process plant. This ratio relates the power pertaining to the fundamental, to the power pertaining to its third harmonic, and hence it can quantify harmonic attenuation or amplification as the oscillation propagates. An oscillatory source can then be isolated provided that low-pass filtering is inherent. The method is demonstrated on both simulated data and real industrial data.

Keywords: Bi-spectrum; Process plants; Oscillations

1. Introduction

It is important for process control engineers to detect and isolate oscillations in a chemical-process operation (Paulonis & Cox, 2003; Qin, 1998). Oscillations can permeate through a plant, increasing variability and preventing a plant from operating close to optimal constraints. They can also camouflage other behaviour that may need attention such as upsets due to external disturbances. A large petrochemical plant may have a 1000 or more control loops and indicators, so a key requirement of an industrial control engineer is for an automated means for the detection of the presence of such oscillations and subsequent to this, for aids to isolate the source of the problem so that maintenance effort can be directed efficiently. This might not be easy, particularly when there are recycle streams present. A common cause of these oscillations is a non-linearity in a control valve (Astrom, 1991; Cook, 1986). In general such non-linearity-induced oscillations contain harmonics: asymmetric triangular waves are often observed in controller outputs (Hägglund, 2002; Rengaswamy, Hagglund, & Venkatasubramanian, 2001) whilst valve stiction often produces square-like waves in the controlled variable. Although both symmetric triangular and pure square waves contain solely odd harmonics, in practice their time series records contain even harmonics also. The bi-amplitude ratio is the ratio of two specific peaks in the bi-spectrum of a signal. It will be shown that this ratio can quantify harmonic attenuation or amplification with respect to the fundamental as an oscillation propagates through a process plant. This leads on to a proposal that the bi-amplitude ratio of each loop should be calculated automatically and an ordered version of this list be presented to the maintenance engineer as an aid to source isolation.

Bi-spectral analysis is attractive because it has the property that it is insensitive to Gaussian noise. The application of bi-spectra to fault identification and condition monitoring is well established, as is its application to the analysis of oscillations in complex systems. For instance, Wang, Wu, and Chen (2001) have used bi-spectra in rotating machinery fault identification. They argue that different faults will have different modal content and hence associate a particular bi-spectrum to a particular fault. The method is very empirical because it involves visual interpretation and relies on the engineer having information about the frequencies that are observed when a certain

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type of fault occurs. Xiang and Tso (2002) have used bi-spectra to *extract* features for concrete flaw detection and classification. Experimental results showed that signals pertaining to the same kind of flaws has significant similarities in their bi-spectral shapes and the location of their peaks, whereas the bi-spectra of other kinds of flaw are considerably different. They produced a neural network, which was trained on distributions of bi-spectra recorded from a number of experiments. The neural network was then used to *classify* three different types of flaws. King (1996) have used the bi-coherence spectrum to determine the presence and extent of non-linear interactions of climate oscillations. Bi-coherence spectra indicate non-linear responses of the climate system to orbital forcing and bi-phase information assists in the quantification of changes in cycle geometry. Komatsu and Spergel (2001) have used bi-spectra to *detect* weak non-Gaussianity in the cosmic microwave background sky. They found that the bi-spectrum was a much more powerful tool for detecting non-Gaussianity than skewness. They also discriminated between bi-spectra that pertained to the primary, the SZ-lensing coupling, and the extragalactic point sources. All the papers above used the bi-spectra as a classification tool; none examined propagation paths.

In a recent paper by Shoukat Choudhury, Shah, and Thornhill (2004), bi-spectrum and bi-coherence methods were applied to process control. They developed two indices for *detecting* and *quantifying* non-Gaussianity and non-linearity: a number of signals involved in plant-wide oscillations would be detected as non-Gaussian and non-linear and their approach could not isolate the source loop.

The method described here pre-supposes that a number of loops have already been detected as oscillatory. Detection should be straightforward: Hägglund (1995) has presented a real-time oscillation detection method that calculates the integrated absolute deviation between successive zero crossings of the controller error signal; Thornhill and Hagglund (1997) have extended Hagglund's zero-crossings idea to an off-line analysis. These two methods assume that the oscillations are symmetric; Forsman and Stratin (1999) have proposed a revision to accommodate the detection of asymmetric and irregular oscillations. Miao and Seborg (1999) have proposed a statistis-based approach, which should perform better than the others in the presence of noise.

The isolation of the root cause of a distributed oscillation has tended to focus on the performance assessment of individual loops, one at a time, until the problem loop is identified. For instance Thornhill and Hagglund (1997) and Horch (1999) have given procedures for the on-line diagnosis of faults in valves and other plant components, whilst McMillan (1995) and Sharif and Grosvenor (1999) have reported methods for the physical testing of control valves. Less work has been carried out to isolate a loop on the basis of measurement time series records collected from controllers and sensors distributed throughout a plant. Thornhill, Shah, and Huang (2001) select the most-likely loop by finding that measurement record that has the maximum distortion factor (D factor), which is a measure of the harmonic content of a record. Xia and Howell (2005) have applied spectral independent-component analysis to the isolation of multiple sources: spectral ICA decomposes a power spectrum into a combination of spectrum-like and single-peak independent components (IC). The ICs can be estimated by finding those vectors which maximize the kurtosis (the fourth-order moment) of each independent component (Xia & Howell 2005). The bi-spectrum can be viewed as a decomposition of the third-order moment (skewness) of a signal. Thus both methods yield information about a signal's non-Gaussinanity.

The bi-amplitude ratio is first outlined in Section 2 and an isolation procedure is proposed. Both simulated-plant data and industrial data are used to illustrate the method in Section 3. Conclusions and future research issues are given in Section 4.

2. The Bi-amplitude Ratio

First and second-order statistics, like the mean, variance, autocorrelation and power spectrum, are popular signal-processing tools and have been used extensively for the analysis of process data. However, second-order statistics like power spectra are unable to represent, unambiguously, the true power of a signal in the presence of Gaussian noise. In contrast, the bi-spectrum, which is associated with higher-order statistics (HOS), can represent a true signal in the presence of Gaussian noise.

2.1. Preliminaries

Non-linearity-induced oscillations often contain a fundamental plus its harmonics, so that, when normalized, a measurement record is composed, primarily, of the sum of a fundamental, its harmonics and random noise:

$$x(n) = \sum_{i=0}^{M-1} \alpha_i \cos(2\pi f_i n + \phi_i) + v(n), \quad 1 \leqslant n \leqslant N, \tag{1}$$

where f_i is the ith discrete frequency, α_i is the amplitude of the ith harmonic, φ_i its phase, M is the number of significant harmonics, $v(n)$ is Gaussian noise with zero mean and variance σ^2 and is uncorrelated with the signal, and N is the data length recorded from the measurement sensor. Note that the f_i's are distinct and that index $i = 0$ corresponds to the fundamental harmonic, $i = 1$ the second harmonic and so on.

The discrete Fourier transformation of each single sinusoidal component is then

$$\begin{aligned} X(f_i) &= F(\alpha_i \cos(2\pi f_i n + \phi_i)) \\ &= \frac{N_f \alpha_i}{2}(\cos\phi_i + j \sin\phi_i)\delta(f - f_i), \\ & \quad i = 0 \ldots, M-1, \end{aligned} \tag{2}$$