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Determining the propagation path of a disturbance in multi-rate process and electromechanical systems

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ABSTRACT

This paper proposes a multi-rate method to identify the propagation path of a persistent disturbance in an enlarged system envelope which includes the process plant and its electromechanical equipment. The need to integrate process and equipment diagnosis has been highlighted by industrial commentators. However, process and electromechanical measurements often have different sampling rates. The multi-rate method proposed extends a state-of-the-art propagation path method so that it combines fast-sampled electromechanical measurements and slow-sampled process measurements. The method is based on non-linear mutual prediction, which yields the directionality in the relationship between two time series. The method was demonstrated and validated, giving the expected outcome in an experimental case study, in which the root cause and propagation path of the disturbance were known.

1. Introduction

In chemical process plants, when a disturbance originates at the root cause, it often propagates through mass and energy flows, and control signals, thus affecting measurements in multiple parts of the plant (Thornhill & Horch, 2007). A common goal in process monitoring and diagnosis is to distinguish the root cause from the propagated disturbances. To that end, a recent topic in the literature is the extraction of the propagation path of the disturbance from measurement data (Yang & Xiao, 2012). The propagation path is a qualitative model of the affected system, and shows the affected measurements in a directed succession according to the order of propagation of the disturbance. Deriving the propagation path allows the root cause to be inferred by tracking the disturbance up the path.

Recently, there have been efforts to integrate process monitoring with the condition monitoring of the equipment and utilities which service the process, in particular to electromechanical equipment (Cecílio, Chen, & Thornhill, 2011, 2014; Lindholm, Carlsson, & Johnsson, 2011). The need for this integration has already been highlighted by several industrial commentators (Reeves, 2005; Schiltz, 2008). The reason is that these auxiliary subsystems interact with the process through energy and signal paths, and hence disturbances can propagate across the subsystems. The aim of this paper is to enable analyses of propagation path in an enlarged system envelope which includes the process and its electromechanical equipment.

Several methods to derive the propagation path of persistent disturbances have been successfully used in operations data of process systems, and some are available in commercial tools (Horch, Cox, & Bonavita, 2007). These methods use advanced signal analysis in order to search for features that arise in the data when a disturbance propagates along a system. Examples of such features include time delays, attenuation, transfer of information, and conditional probability relations. Examples of methods include the quantification of the nonlinearity of time series (Thornhill, 2005), the transfer entropy between two time series (Bauer, Cox, Caveness, Downs, & Thornhill, 2007a; Naghoosi, Huang, Domlan, & Kadali, 2013), and the non-linear mutual prediction between two time series (Bauer, Cox, Caveness, Downs, & Thornhill, 2007b; Stockmann, Haber, & Schmitz, 2012).

However, the current methods are applicable only to uni-rate systems, that is, systems whose measurements are all available with the same sampling rate. Systems with process and electromechanical measurements, on the other hand, are often multi-rate because process measurements are usually sampled approximately 1000 times slower than electromechanical measurements. Therefore, to apply the current methods, the electromechanical measurements have to be downsampled to the process rate.

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However, downsampling may compromise the accuracy of the results. For instance, if the duration of the disturbance is shorter in the electromechanical measurements than in the process measurements, the slow process sampling rate may be enough to capture the disturbance in the process measurements but not in the electromechanical measurements. Such data sets would require the combined analysis of fast-sampled electromechanical measurements with slow-sampled process measurements.

The contribution of this paper is the adaptation of method by Bauer et al. (2007b) for the determination of the propagation path of a persistent disturbance. The adaptation enables the combined analysis of electromechanical and process measurements. The paper uses experimental data from a gas compressor rig to benchmark the results yielded with the new multi-rate method with the results of the uni-rate method by Bauer et al. (2007b).

The paper is structured as follows. Section 2 presents the experimental case study and underlying physical models for validating the method. Section 3 provides background on non-linear mutual prediction. Section 4 explains the algorithm for the multi-rate method, which is then tested and compared to the uni-rate method by Bauer et al. (2007b) in Section 5. Section 6 closes with conclusions.

2. Compressor rig experiments and physical modelling

2.1. Compressor rig experimental case study

To validate the proposed method, the paper uses a case study in which the root cause of the disturbance is known and the expected propagation path is derived from a model of the system. The case study consists of measurement data from experimental work with a gas compressor rig located at ABB Corporate Research Center, Kraków, Poland. The main components of the rig are a compressor, an induction motor and an a.c. voltage–source inverter drive. Fig. 1 shows the rig schematically. On the process side, the measured variables relevant to this paper are the tank pressure, p_t, and the flow through the compressor, m_c. The electromechanical variables are measured in the drive and include the shaft speed set-point, ω^*, the shaft speed, ω, and the electromagnetic torque in the motor, τ_e.

Fig. 2 shows time series of the five measurements, all available at 1 kHz. The time series show a train of pulses induced in the set-point ω^* of the shaft speed. The deviations in the time series of the other measurements result from the propagation of the set-point disturbance. The order of the measurements in the plot reflects, from top to bottom, the propagation path of the disturbance. This expected propagation path is derived from the model of the system in Section 2.3.

2.2. Changes in a propagating disturbance

When a disturbance propagates along a system, its effect on the disturbed system variables changes due to the dynamic

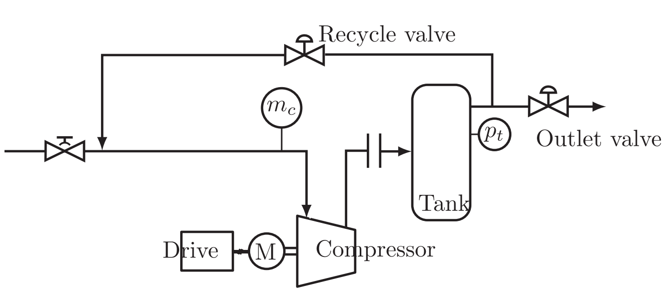

Fig. 1. Simplified schematic of the gas compression rig.

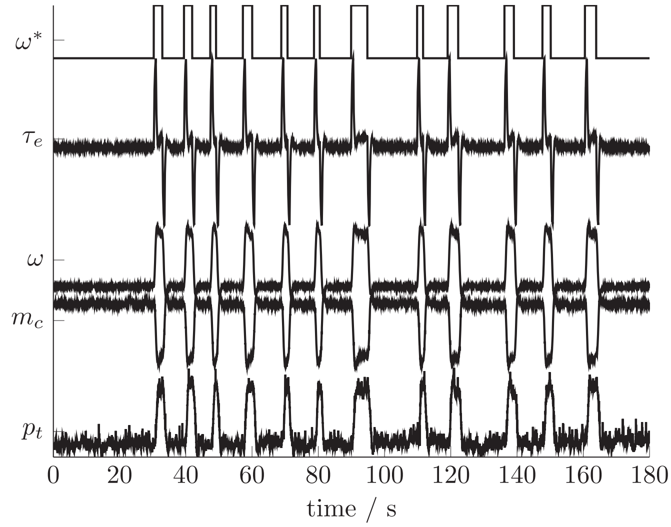

Fig. 2. Time series of the original fast-sampled measurements in the case study.

Table 1
Common changes in a propagating disturbance due to dynamic characteristics of the system.

Change	Underlying dynamic characteristic
Time lag between the disturbance in the measurements of two variables	Dead time
Low pass filtering, *i.e.* smoothing of the disturbance trend	Time constant
Decrease in the disturbance magnitude	Gain smaller than one
Addition of noise	Measurement noise or outside influences

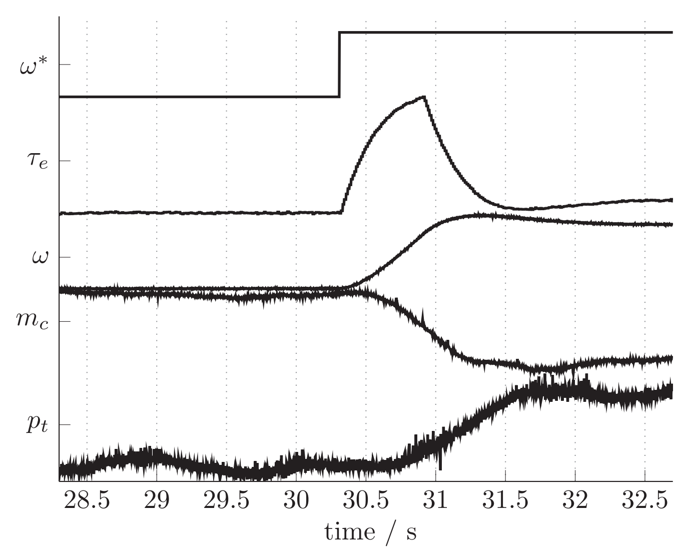

Fig. 3. Close-up on the start of a disturbance induced with the set-point ω^*. The sequence of plots reflects, from top to bottom, the propagation path of the disturbance.

characteristics of that system. Table 1 indicates four changes which are commonly observed.

Fig. 3 shows a close-up on the measurements of the case study so that these changes can be observed. The start of the disturbance is seen after the 30 s time instant. The effect of additional time constants is best observed from measurement ω^* to τ_e, and from τ_e to ω, whereas the effect of dead time is best observed from measurement ω to m_c, and from m_c to p_t. Methods which are