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Development of soft sensors for permanent downhole Gauges in deepwater oil wells

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ABSTRACT

Downhole pressure is an important process variable in the operation of gas-lifted oil wells. The device installed in order to measure this variable is often called a Permanent Downhole Gauge (PDG). Replacing a faulty PDG is often not economically viable and to have an alternative estimate of the downhole pressure is an important goal. Using data from operating PDGs, this paper describes a number of issues dealt with in the development of soft sensors for several deepwater gas-lifted oil wells. Some of the tested models include nonlinear polynomials, neural networks, committee machines, unscented Kalman filters and filter banks. The variety of model classes used in addition to the diversity of oil wells considered brings to light some of the key-problems that have to be faced and reveal the strengths and weaknesses of each alternative solution. A major constraint throughout the work was the use of historical data, hence no specific tests were performed at any time. The aim of this work is to discuss the procedures, pros and cons of the tested solutions and to point to possible future directions of research.

1. Introduction

In gas lift wells, high pressure gas is injected downhole into the tubing and mixes with the fluid coming from the reservoir. The injected gas reduces the hydrostatic pressure in the tubing facilitating production in scenarios with low reservoir pressure. The gas flow rate is a key factor in the well productivity and many other operational aspects. In many platforms, the gas flow rate is determined based on the downhole pressure which is considered by some authors to be the most important variable to describe the dynamics of an oil well (Nygaard, Naevdal, & Mylvaganam, 2006). Hence, permanent downhole monitoring plays an important role in several aspects of gas and oil industries, such as operation safety, production performance and planning (Algeroy, Lovell, Tirado, Meyyappan, Brown, Greenaway, Carney, Meyer, Davies, & Pinzon, 2010). In the context of the present study, downhole pressure is planned for future anti-slugging control (Campos, Von Meien, Neto, Stender, Takahashi, & Ashikawa, 2015) and also for short-term production optimization, using gas-lift as manipulated variable (Campos, Teixeira, Von Meien, Simes, Santos, Pimenta, & Stender, 2013). In most instances, replacing a faulty downhole probe is not economically viable and the development of soft sensors emerges as an interesting alternative (Antonelo, Camponogara, & Foss, 2016).

Since its early days (Upadhyaya & Eryurek, 1992), soft sensing has become an important topic in todays competitive technology in several applications and fields of research (Fortuna, Graziani, Rizzo, & Xibilia, 2007; Kadlec, Grbic, & Gabrys, 2011; Khatibisepehr, Huang, & Khare, 2013; Mandenius & Gustavsson, 2015). The central idea is to build mathematical models that, taken individually or in the context of state estimators, would provide an estimate of the desired variable based on a set of available measurements. The number of possibilities is overwhelming, not only in what concerns the model class which ranges from simple algebraic equations to committees of complex nonlinear dynamical models, but also with respect to the estimation philosophy which can be a forward mapping achieved by FIR (finite impulse response) models, or iterative open-loop estimation such as attained by IIR (infinite impulse response) models, or even closed-loop schemes that perform some sort of data assimilation as implemented by observers (Jahanshahi, Salahshoor, & Sahraie, 2008) and filtering schemes (Nygaard et al., 2006).

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The main objective of this work is to describe some of the chief issues that were encountered in developing soft sensors using historical data for the downhole pressure of several gas-lifted oil wells. One of such issues is related to the time-varying character of the plant. It is argued that state estimation methods and gray-box identification can be used to mitigate such a problem. The techniques described in the paper are also applicable in situations where time-variation is not so critical.

Although most permanent downhole probes include both pressure and temperature sensors, this work is almost exclusively devoted to the former. A particular aspect that will be highlighted is the use of steady-state data as a source of auxiliary information. Hence gray-box system identification techniques (Aguirre, Barroso, Saldanha, & Mendes, 2004; Nepomuceno, Takahashi, & Aguirre, 2007) were used to *simultaneously* employ dynamical and steady-state data in the estimation of NARMAX (nonlinear autoregressive moving average models with exogenous inputs) polynomial and neural models (Billings, 2013). Other important aspects of this paper include the use of Kalman-based filter banks and of neural-based committee machines. In a recent work, echo state networks were used to provide estimates of the downhole pressure based on surface measurements (Antonelo et al., 2017).

The remainder of this paper is organized as follows. In Section 2 a brief description of the process is provided. The important problem of which variables to choose to compose the models is discussed in Section 3, and the selection of dynamical and static data sets in addition to the detection of outliers and data clustering is described in Section 4. The development of mathematical models by means of system identification techniques is described in Section 5. The estimation of downhole pressure is addressed in a state estimation framework in Section 6 where both single filter and filter banks solutions are compared. Model validation procedures and issues related to time-varying features of the process are discussed in Section 7. The developed soft sensors were implemented in software, as described in Section 8. Final remarks and future developments are provided in Section 9. Fig. 1 presents an overview of the methodology used in this paper to build downhole pressure soft sensors.

2. Process description

This section is based on (Teixeira, Castro, Teixeira, & Aguirre, 2014). Fig. 2 presents a simplified diagram of a gas-lift oil well and Table 1 lists some of the process variables often measured. The PDG probe provides pressure (PT1) and temperature (TT1) measurements.

High pressure gas coming from the gas-lift header at the platform (instruments tagged by 4) is injected through annulus between tubing and casing string until it reaches an orifice valve located downstream in the lower part of the tubing. The fluid density is then reduced such that the reservoir pressure is high enough to transport the multiphase mixture of oil, gas, water to the platform. In the seabed, a set of valves and adapters known as wet Christmas tree control the production flow from seabed to the platform. In the platform, a shutdown valve is available to interrupt the production during an emergency situation and a choke production valve regulates the production flow rate at the platform. Different flow dynamics are achieved depending on the values gas-lift (PT4 and PT4a) and downhole (PT1) pressures.

In order to develop soft sensors for PT1 historical data available from a SCADA (Supervisory Control and Data Acquisition) system was acquired, with sampling time of $T_s = 1$ min. This sampling time is adequate for the intended use of the downhole pressure measurement, namely anti-slug control (Campos et al., 2015) and short-term production optimization (Campos et al., 2013).

3. Variable selection

One of the key problems in developing soft sensors for the downhole pressure is the choice of which variables to choose as inputs. A standard procedure in the choice of explanatory variables for composing a

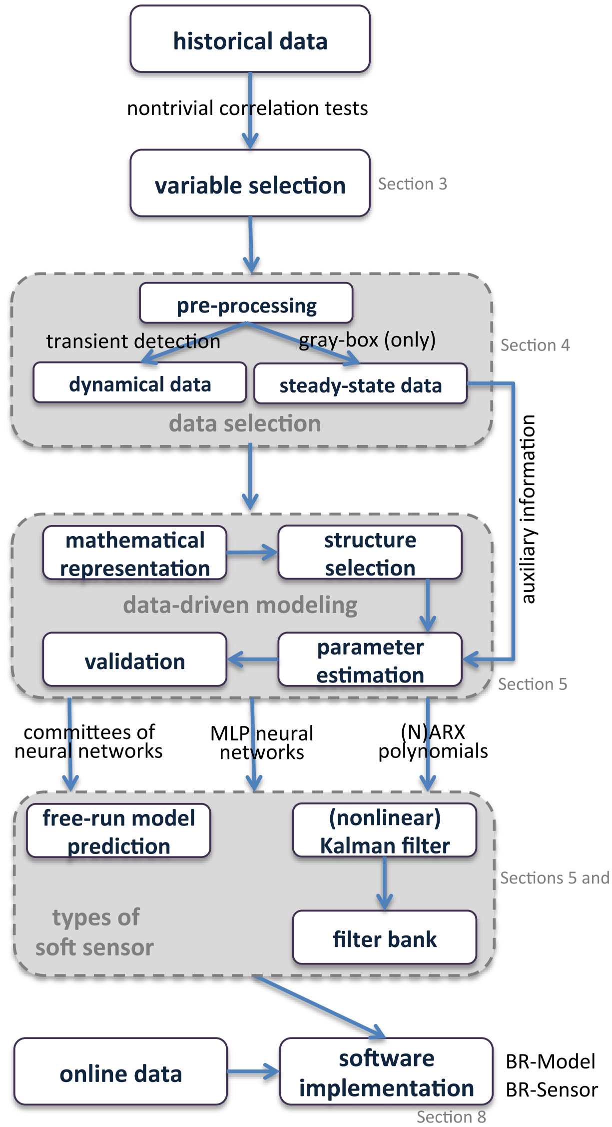

Fig. 1. Overview of the methodology used to develop downhole pressure soft sensors from historical data. The steps indicated are discussed throughout the paper.

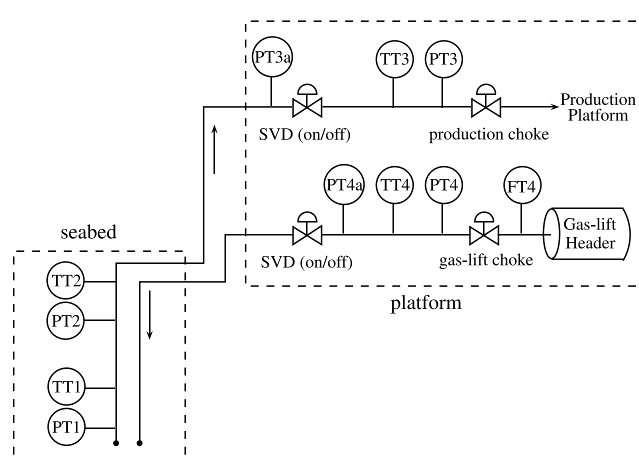

Fig. 2. Simplified P&ID diagram of a gas-lifted oil well, where TT refers to temperature transmitters and PT refers to pressure transmitters. The numbers 1 (downhole) and 2 (wet Christmas tree) accounts for downhole and seabed variables, while 3 (production) and 4 (gas lift) accounts for platform variables.