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State estimation of transient flow in gas pipelines by a Kalman filter-based estimator

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ABSTRACT

In this study, real-time estimation of flow rate and pressure along natural gas pipelines under transient flow condition is aimed. The estimation of the internal states of gas pipelines is based on a recursive discrete data filtering algorithm called the discrete Kalman filter. The state space representation of the transient flow in gas pipelines, which is required for the filtering algorithm, is established by a discrete form of the nonlinear partial differential equations (PDE's) describing the characteristics of transient gas flow. The PDE's are discretized by the finite element method and an implicit scheme is employed in order to obtain a simple and adequate algebraic set of equations for the transient gas flow. The state estimator uses these linearized equations and the estimation phase is performed using simulated data imitating measurements. The motivation of this work is to estimate the actual state of the flow with the online data by applying the discrete state-space model of the flow. Therefore, the estimator is developed for a situation where pressure measurements at a few points along the pipe and one flow rate data at the outlet end of the pipe are available. Moreover, to improve the performance of the estimator, the state estimation with a pair of Kalman filter based estimators running in parallel is also proposed. The performance of state estimations is tested on a case study from the literature. The developed estimator can predict the simulated states even with incomplete and/or faulty information on the system parameters.

1. Introduction

Pipelines that transport natural gas are always subject to certain transients. The transients may arise from consumer demand change, operational failures, changing of system control strategies. Therefore, the system controllers (dispatchers) need to simulate the gas flow in unsteady flow conditions. However, a well-posed simulation requires the exact initial state (pressure and flow rate profile), the imposed boundary conditions (time-varying demand, supply and pressure at the end points of the pipe) and the system characteristics (the diameter of pipeline, the friction factor, the properties of flowing gas), which are unfortunately hard to obtain exactly. Besides, the data acquisition, which provides measurements used mostly as boundary conditions, may be prone to inaccuracy and noise. Such difficulties make the simulations susceptible to potential errors. On the other hand it is possible to collect data from the system not only at the pipeline inlet and outlet but also along the pipeline. Nonetheless, those data may not be utilized in standard simulators.

Simulators solve numerically the transient gas flow problems in pipelines. Several methods that solve this problem are available in the literature. For example, the finite difference methods, the finite element methods, or the method of characteristics. Taylor et al.'s study (1962) was one of the earliest that develops a computational model for transient flow in gas pipelines. Developing such models have been the subject of intensive study for the following decades. Among the notable studies of this period, Zhou and Adewumi (2000) applied an explicit first-order accurate scheme with three points, and a second-order scheme with five points to simulate transient flow in natural gas pipelines. Emara-Shabaik et al. (2004) developed a simulator using a predictor–corrector approach with centered-space discretization scheme which involves explicit time integration. Alamian et al. (2012) first linearized the governing pipe flow equations using dimensionless variables, then transformed the linearized equations into ordinary differential equations and applied them in their pipe flow simulation models. Helgaker (2013) presents an extensive literature review related to modeling of transient flow in offshore natural gas pipelines.

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The state estimation in real-time for gas pipelines has been accomplished by matching simulator's output with measured information from SCADA (Supervisory Control and Data Administration) systems (Ellul, 1988; Turner et al., 1991). The real-time state estimation in a contemporary large scale gas transportation network requires a parameter estimation approach (called as Maximum Likelihood State Estimator) by solving a weighted sum-of-squares difference between modelled flow equations and available measurement data for the pressures and flow rate (Velde et al., 2013).

Although deterministic models that describe the transient gas flow phenomena have been widely studied, the state estimation problem has been rarely solved by the systems theory approach. Lappus and Schmidt (1980) proposed parallel simulation and observer schemes. They assumed that the flow rates at the inlet and the outlet points are known. Durgut and Leblebicioğlu (1997) tackled the estimation problem around optimal control strategies. Reddy et al. (2006) proposed using the approximate transfer function (Kralik et al., 1984) for the real-time state estimation in gas pipelines. Emara-Shabaik et al. (2002) have used an extended Kalman filter for the purpose of leak detection in gas pipelines using the backward time-centered space discretization of the flow equations. However, the prediction error covariance matrix P, and in turn, for the Kalman filter gain matrix K excluded the nonlinear terms of the system equations. Therefore, the benefit of applying the extended Kalman filter is not obvious. Moreover they considered that the flow rate measurements are available at several points along the pipe, which is not a feasible and practical situation. Sanada (2012) applied a Kalman filter to compare the estimated flowrate with the flow rate measurement of a very short pipeline (3.2 m) at a single point. Recently Behrooz and Boozarjomehry (2015) applied the continuous/discrete form of the extended Kalman filter in state estimation for gas transmission networks, after transforming the pipe flow equations into the ODE's based on a few collocation points.

The state estimation in terms of pressure and flow rate along the pipe has importance in real-time flow balance calculations, leak detection and state estimation for each pipeline segment of the transportation systems.

In the present paper, the state-space estimation of compressible transient flow in a gas pipeline is addressed. Transient, one-directional and isothermal gas flow in a pipeline is defined mathematically by a set of nonlinear PDE's. The discrete state-space model is specifically obtained by a finite element approximation of the transient gas flow equations in the pipeline. In this way, the state estimation could be performed on that model by the Kalman filter applying pressure measurements at a few points along the pipe and one flow rate data at the outlet end as opposed to the imposed boundary conditions in simulations. The algorithm is tested on a simulated pipeline, which was subject to certain transients. The developed estimator can estimate the state of pipeline even when the system parameters are incomplete and/or faulty. Moreover, for improved performance, the state estimation with a pair of Kalman-filter based estimators running in parallel is also proposed and evaluated.

2. System model

The principal elements of natural gas transportation systems are pipelines, which dominate the major dynamic characteristics of the systems. The dynamics of the compressible transient flow in gas pipelines and its model are described below.

2.1. System description

When gas is flowing through a pipe it is subject to frictional forces, which result in pressure drop. Under uniform flow rate conditions (i.e., steady flow everywhere along the pipeline) the pressure drop through the pipeline is estimated by analytical relationships. However the steady-state flow regime in a pipeline can be easily disrupted due to changes in customer demand, supply of gas companies and other operational activities. These disturbances may occur at either end of pipeline and are usually treated as boundary conditions. In this study the boundary conditions, which control the system, are defined as the inlet pressure and the outlet flow rate. Any changes in these variable result in transients in gas flow. Moreover, compressible nature of the gas makes the pressure and flow along the pipeline easier to attain the transient flow characteristics.

2.2. State space representation

The mathematical modeling of transient flow in gas pipelines is based on a system of partial differential equations. These basic differential equations are of the non-linear, hyperbolic, first order type. They are derived from the mass and momentum conservation principles as well as the mechanical energy balance. Furthermore, the derivation also involves an equation of state relating the given quantity of the gas to the pressure, the volume, the temperature and the deviation factor from ideal-gas behavior. The mathematical model is constructed by considering isothermal, one dimensional, (1-D) and turbulent flow. For 1-D pipe flow, pressure, density, velocity or mass flow rate are only function of time and space (distance along the axis of the pipe). Therefore, the state-space model of the transient gas flow is written in the form:

$$\frac{\partial p(x,t)}{\partial t} + a\frac{\partial m(x,t)}{\partial x} = 0, \tag{1}$$

$$\frac{\partial m(x,t)}{\partial t} + b\frac{\partial p(x,t)}{\partial x} + c\frac{m(x,t)|m(x,t)|}{p(x,t)} = 0, \tag{2}$$

with the dependent variables the mass flow rate $m(x,t)$ and the pressure $p(x,t)$ along the pipe. In the momentum equation, it is assumed that the pipeline is horizontal therefore, the gravitational term drops out. The convective term has been neglected since the space derivative of the flow rate is negligible compared to other terms. The physical parameters of the governing equations are grouped to obtain the base parameters:

$$a = \frac{B^2}{A}, \quad b = A, \quad c = \frac{f}{2D}a, \tag{3}$$

where A is the cross-sectional flow area of the pipe, B is the acoustic velocity in the gas, f is the Darcy friction factor, D is the pipe diameter.

A unique solution to these equations is provided by a prescribed initial condition as well as boundary conditions. Steady-state flow regime is assumed as the initial condition, that is, the states known at the initial time, t_0 (for the sake of convenience, taken as $t_0 = 0$). Since the mass rate at t_0 is constant (i.e., $m(x,0) = m_0$), the steady-state flow relationship yields the initial pressure distribution along the pipeline, $p(x,0) = p_0(x)$. Moreover, the pipeline is subject to a known time-varying demand $\alpha(t)$ and the inlet pressure $\beta(t)$. In brief, Eqs. (1) and (2), have the initial conditions

$$m(x,0) = m_0, \tag{4}$$

$$p(x,0) = p_0(x) \tag{5}$$

and the boundary conditions