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Dual Modal Imaging of Two-Phase Flows Using Electromagnetic Flow Tomography and Electrical Tomography – State Estimation Approach

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Introduction

Accurate estimation of two-phase flow quantities such as phase fraction, velocity field, and volumetric flow rate of each phase is often required for, e.g., process control, automation, product quality improvement, and production cost lowering. There have been many advances in industrial tomographic imaging systems over the years. Recently, dual-modality imaging has attracted attention because single modality systems are often incapable of quantifying all relevant flow parameters. This paper discusses the development of a novel dual modal imaging system consisting of electromagnetic flow tomography (EMFT) and electrical tomography (ET) [1], and more specifically, the joint reconstruction of flow quantities based on these modalities using Bayesian state estimation [2].

State-space model and joint reconstruction

For state estimation, we write the so-called state-space representation of the system – it consists of the observation models of EMFT and ET, and evolution models for the time-dependent state variables (here, the phase fraction distribution and velocity field).

In EMFT, the multiphase fluid flowing in a pipe is exposed to an external magnetic field, which causes a Lorentz force on the electrically conductive fluid, and the resulting electric potentials are measured on electrodes attached on the surface of the pipe. We approximate the associated partial differential equation and boundary conditions with the finite element method (FEM). This leads to the following observation model for EMFT

$$U = H(\phi)v_z + e_v, \tag{1}$$

where U is a vector consisting of electrode potentials, H is the forward operator, and ϕ is the spatially distributed phase fraction of the dispersed phase; it affects the potentials through the dependence of the electrical conductivity σ on it, $\sigma = \sigma(\phi)$. Further, v_z is the axial component of the velocity field, and e_v is the additive observation noise [3].

In ET, we use the voltage-current (VC) [4] system where electric currents resulting from potential excitations on a set of electrodes are measured. Again, FEM is used for approximating the solution of the associated boundary value problem, leading to an observation model

$$I = R(\phi) + e_\phi, \tag{2}$$

where R is the forward operator of ET, which again, includes the model $\sigma = \sigma(\phi)$, and e_ϕ is observation noise.

Defining a new variable $\theta = [\phi^T \; v^T]^T$ which includes all the model unknowns in EMFT and ET, we express Equations (1) and (2) in a concatenated form

$$\boldsymbol{y}_t = \boldsymbol{h}(\theta_t) + e_t. \tag{3}$$

where $y = [U^T \ I^T]^T$ and $e = [{e_v}^T \ {e_\phi}^T]^T$. Since the state variable θ depends on time and $\boldsymbol{y}$ is measured sequentially, we have here used the notation of a discrete time index t. Furthermore, we model the time-dependences of ϕ and v_z by a stochastic convection-diffusion (CD) model [5] and a first-order Markov model, respectively. The FEM approximations of these surrogate models lead to an evolution model

$$\theta_{t+1} = f(\theta_t) + \omega_t, \tag{4}$$

where f is the state transition operator and ω_t is the state noise process. Based on the state-space representation (Equations (3) and (4)), the state variable is estimated using extended Kalman filter (EKF) and the fixed-interval Kalman smoother (FIKS).

Results

The performance of the proposed state estimation in dual-modality EMFT-ET is evaluated using a set of numerical simulations and further validated by experimental data. In these studies, the state estimates (especially FIKS) outperform the conventional stationary reconstructions in EMFT and ET. The proposed dual modal imaging system is expected to be applicable to industrial processes that involve for example oil-water flows.

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