Dual modal imaging of two-phase flows using electromagnetic flow tomography and electrical tomography – state estimation approach

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Abstract

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 and product quality improvement. 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 representation of the system 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. By using the finite element method (FEM) for the approximation, the observation model for EMFT is in the form

$$U = H(\sigma(\phi))\upsilon_z + e_{\upsilon_z}, \tag{1}$$

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. Further, υ_z is the axial component of the velocity field, and e_z is the additive observation noise [3]. In ET, we use the voltage-current (VC) system and the observation model is in the form

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

where R is the forward operator of ET and e_ϕ is observation noise.

Defining a new variable $\theta = [\phi^T \upsilon^T]^T$, we express Equations (1) and (2) in a concatenated form

$$\mathbf{y}_t = \mathbf{h}_t(\theta_t) + e_t, \tag{3}$$

where $\mathbf{y} = [U^T I^T]^T$ and $e = [e_\upsilon^T e_\phi^T]^T$ and t is a discrete time index. Furthermore, we model the time-dependencies of ϕ and υ_z by a stochastic convection-diffusion (CD) model [4] and a first-order Markov model, respectively. The FEM approximations of these surrogate models lead to an evolution model

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

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).

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.

References

[1] M. Ziaul Arif, et al. "Joint reconstruction of conductivity and velocity in two-phase flows using electromagnetic flow tomography and electrical tomography: A simulation study." IEEE Transactions on Instrumentation and Measurement 70 (2021): 1-17.

[2] M. Ziaul Arif, A. Seppänen, M. Vauhkonen: "State estimation approach to dual-modal imaging of two-phase flow based on electromagnetic flow tomography and electrical tomography", submitted.

[3] Ossi Lehtikangas, K. Karhunen, and M. Vauhkonen, "Reconstruction of velocity fields in electromagnetic flow tomography," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 374, no. 2070, p. 20150334, 2016.

[4] Aku Seppänen, M. Vauhkonen, P. Vauhkonen, A. Voutilainen, and J. Kaipio, "State estimation in process tomography—three-dimensional impedance imaging of moving fluids," International journal for numerical methods in engineering, vol. 73, no. 11, pp. 1651–1670, 2008.