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Multi-phase flow monitoring with electrical impedance tomography using level set based method

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HIGHLIGHTS

- LSM has been used for shape reconstruction to monitor multi-phase flow using EIT.
- Multi-phase level set model for conductivity is represented by two level set functions.
- LSM handles topological merging and breaking naturally during evolution process.
- To reduce the computational time, a narrowband technique was applied.
- Use of narrowband and optimization approach results in efficient and fast method.

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ABSTRACT

In this paper, a level set-based reconstruction scheme is applied to multi-phase flow monitoring using electrical impedance tomography (EIT). The proposed scheme involves applying a narrowband level set method to solve the inverse problem of finding the interface between the regions having different conductivity values. The multi-phase level set model for the conductivity distribution inside the domain is represented by two level set functions. The key principle of the level set-based method is to implicitly represent the shape of interface as the zero level set of higher dimensional function and then solve a set of partial differential equations. The level set-based scheme handles topological merging and breaking naturally during the evolution process. It also offers several advantages compared to traditional pixel-based approach. Level set-based method for multi-phase flow is tested with numerical and experimental data. It is found that level set-based method has better reconstruction performance when compared to pixel-based method.

1. Introduction

Flow through pipe that contains single or multi-phase is observed in many industrial applications. For example, flow in heat exchangers, fluidized bed, oil transportation, pneumatic conveying etc. The phase distribution inside the pipe tells us about the actual process therefore it helps in the monitoring of the process and also affects the safety operation of mechanical systems. It is necessary to find a method to obtain the flow characteristics without disturbing the flow process. Electrical impedance tomography (EIT) is a non-intrusive and non-destructive image reconstruction technique that offers high temporal resolution characteristics therefore it has been a hallmark in process tomography applications to determine the flow characteristics (Jain et al., 1997; Jones et al., 1993; Brown, 2001). In EIT, electrical current is passed through the electrodes that are discreetly placed around the object to be imaged and the resulting excitations caused due to the presence of the medium inside the domain are measured on the surface of electrode. Based on the current–voltage relationship, internal distribution inside the object is reconstructed. EIT image reconstruction can be summarized into forward and inverse problem. The forward problem of EIT calculates the boundary voltages and internal potential distribution based on given conductivity distribution and injected currents. The inverse problem reconstructs the impedance distribution from the boundary voltage measurements. In multi-phase flow process, in many situations, the knowledge of the conductivities of the anomalies is known *a priori*. The prior information of the conductivities can be used in the inverse algorithm to estimate the size, shape

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and location of the anomalies for monitoring multi-phase flow (Kolehmainen et al., 1999; Liu et al., 2015a,b).

Shape reconstruction has been studied by many researchers and several methods are proposed to represent the shape of the anomalies occurring in flow process (Aparicio and Pidcock, 1996; Kang et al., 1997; Beretta and Vessela, 1998; Kolehmainen et al., 1999; Tamburrino et al., 2003; Tossavainen et al., 2006; Khambampati et al., 2010; Rashid et al., 2011). Level set method has emerged recently as an attractive alternative technique to solve topology optimization problems (Osher and Sethian, 1988). A level set representation can describe concisely the geometric and material boundaries of an anomaly, for example, it can be used to represent or identify piecewise constant or piecewise smooth functions of the inclusions (Vese and Chan, 2002). More importantly, it has strong ability to accommodate shape related topological changes, especially merging or splitting of the components. Meantime, level set method has become powerful and versatile tool for image processing and computational physics (Vese and Chan, 2002; Osher and Fedkiw, 2001, 2003; Chung et al., 2005), also it has found applications in shape reconstruction and inverse scattering (Dorn et al., 2000; Dorn and Lesselier, 2006). More recently, applications of level set method to electrical tomography (ET) problems have been proposed (Ito et al., 2001; Soleimani et al., 2006a,b; Rahmati et al., 2012; Rahmati and Adler, 2013). In Ito et al. (2001), using values of Neumann data as well as values of solution in a thin layer along the domain, level set method together with steepest descent method has been employed to solve the inverse conductivity problem. In Soleimani et al. (2006a), narrow band level set method combined with Gauss–Newton as an inverse algorithm was used to estimate the shape and location of two-phase flow. In Soleimani et al. (2006b), a similar method as in Soleimani et al. (2006a) was employed using EIT to imaging of the human brain. Most of the work discussed before are related to the reconstruction of two-phase cases. In real situations, more than two phases can exist therefore multi-phase reconstruction will provide better visualization of the flow characteristics.

In this paper, a level set-based method (LSM) for shape reconstruction using EIT is presented. Multi-phase reconstruction is done where the conductivity values of the inhomogeneous background and that of anomalies are known, and the size, shape and location of the anomalies are unknown. Gauss–Newton method based on level set method in (Soleimani et al., 2006a) and multi-phase framework for image segmentation in (Vese and Chan, 2002; Yanovsky et al., 2007) are employed into multi-phase shape reconstruction. In using a multi-phase level set model, the conductivity distribution can be represented by two level set functions. Based on the level set theory, the key idea was to implicitly represent the shape of interface as the zero level set of a higher dimensional function, and then solve a set of partial differential equations (PDEs) in the Cartesian coordinate system which contains the shape of this new embedding function (Chen et al., 2009). The shape is set as the zero level set of higher dimensional functions, so the computational cost and time will increase. In order to reduce the computational time, a narrowband technique was applied to calculate the shape deformation or update. The combination of the narrowband technique and optimization approach results in a computationally efficient and fast method for solving the inverse problem. Numerical and experimental experiments are performed to evaluate the performance of the proposed method.

2. Shape reconstruction using level set method

In this section, the shape parameterization using level set method is presented. In Vese and Chan (2002) up to 2^m distinct regions of the form $\bigcap_{j=1}^{m}\{\pm\phi_j > 0\}$ can be represented by m level set functions ($\phi_1, \phi_2, \phi_3, \ldots, \phi_m$). For simplicity of presentation, we assume the domain Ω contains three different regions (Fig. 1) which do not have overlapping and vacuum state with piecewise constant conductivities $\sigma = (\sigma_0, \sigma_1, \sigma_2)$, where σ_0, σ_1 and σ_2 are three positive real numbers.

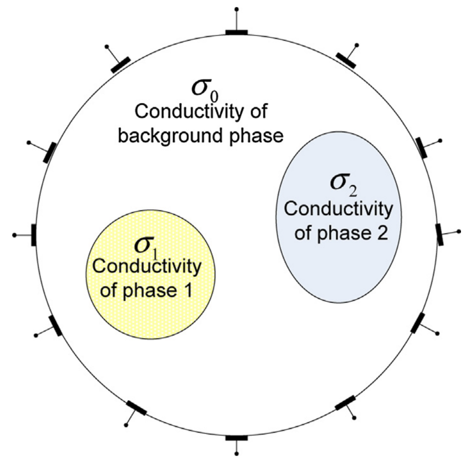

Fig. 1. Shape reconstruction of multi-phase flow using EIT.

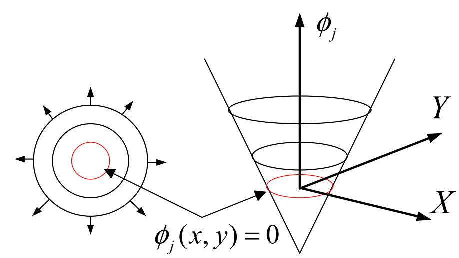

Fig. 2. Representation of the contours of the objects as the zero level set of a level set function.

In association with the three regions represented by two level set functions $\phi = (\phi_1(x, y), \phi_2(x, y))$ describes the interior conductivity distribution $\sigma(x, y)$ in Ω as follows.

$$\sigma = \sigma_0 H(\phi_1)H(\phi_2) + \sigma_1(1 - H(\phi_1))H(\phi_2) + \sigma_2(1 - H(\phi_2))H(\phi_1) \tag{1}$$

where $H(s)$ is the Heaviside function, defined as

$$H(s) = 1 \quad \text{for} \quad s \geq 0, \quad H(s) = 0 \quad \text{for} \quad s < 0. \tag{2}$$

and $\phi = (\phi_1(x, y), \phi_2(x, y))$ is the level set function satisfying

$$\begin{aligned} \Omega_1 &= \{(x, y) \in \Omega | \phi_1(x, y) < 0, \quad \phi_2(x, y) > 0\} \\ \Omega_2 &= \{(x, y) \in \Omega | \phi_1(x, y) > 0, \quad \phi_2(x, y) < 0\} \end{aligned} \tag{3}$$

Then we can write

$$\nabla\sigma = g_1(\phi_2) \cdot \nabla H(\phi_1) + g_2(\phi_1) \cdot \nabla H(\phi_2) \tag{4}$$

where

$$\begin{aligned} g_1(\phi_2) &= (\sigma_0 - \sigma_1)H(\phi_2) + \sigma_2(1 - H(\phi_2)) \\ g_2(\phi_1) &= (\sigma_0 - \sigma_2)H(\phi_1) + \sigma_1(1 - H(\phi_1)) \end{aligned} \tag{5}$$

Let $\Gamma_j (j = 1, 2)$ be the interface between two different regions, which is also a boundary of the region, is given by the zero level set (Fig. 2)

$$\Gamma_j := \{(x, y) : \phi_j(x, y) = 0\} \tag{6}$$

If we change this level set function by a small distance, we assume the update is sufficiently smooth, such that the basic