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Reconstruction of electrical capacitance tomography images based on fast linearized alternating direction method of multipliers for two-phase flow system☆

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ABSTRACT

Electrical capacitance tomography (ECT) has been applied to two-phase flow measurement in recent years. Image reconstruction algorithms play an important role in the successful applications of ECT. To solve the ill-posed and nonlinear inverse problem of ECT image reconstruction, a new ECT image reconstruction method based on fast linearized alternating direction method of multipliers (FLADMM) is proposed in this paper. On the basis of theoretical analysis of compressed sensing (CS), the data acquisition of ECT is regarded as a linear measurement process of permittivity distribution signal of pipe section. A new measurement matrix is designed and L1 regularization method is used to convert ECT inverse problem to a convex relaxation problem which contains prior knowledge. A new fast alternating direction method of multipliers which contained linearized idea is employed to minimize the objective function. Simulation data and experimental results indicate that compared with other methods, the quality and speed of reconstructed images are markedly improved. Also, the dynamic experimental results indicate that the proposed algorithm can fulfill the real-time requirement of ECT systems in the application.

1. Introduction

Two-phase flow is a mixed-flow pattern widely found in nature, especially in chemical, petroleum, electricity, nuclear power and metallurgical industries [1,2]. Two-phase flow image reconstruction plays an increasing important role in the automation of energy industry. In recent years, process tomography (PT) technology has been developed rapidly, and it has great potential and broad prospects in solving the two-phase flow detection problems for industrial applications. Among various tomography techniques such as X-ray, electrical, ultrasonic, nuclear magnetic resonance, and microwaves, the tomography technique based on measurement of electrical properties has received significant attention [3,4]. Electrical Resistance Tomography (ERT) [5], Electromagnetic Tomography (EMT) [6], and Electrical capacitance tomography (ECT) [7] constitute the three main types of electrical-based tomography techniques. ECT provides the permittivity distribution across the two-phase flow by measuring the capacitances between all pairs of electrodes surrounding this flow in a relatively short time. Compared with other tomography techniques, ECT is a relatively new and has some distinct advantages: being safe (*i.e.* non-radioactive), non-invasive, lower cost, portable and much faster. Thus, it can be adopted for applications requiring real-time performance such as visualization of oil–water pipeline flows and gas–solid flows. Since the ECT system is a typical nonlinear system, the measurements from independent capacitance (projection data) are limited and rare, far less than the number of pixels of the reconstructed image. Besides, the ECT inversion problem has no analytical solution. At the same time, since ECT has some essential properties such as nonlinear and"soft field", the stability of solution of ECT systems is bad and there is a serious morbidness [8–10].

The successful application of ECT measurement is largely dependent on the speed and accuracy of imaging reconstruction algorithms. Now there are more commonly used methods for ECT image reconstruction, such as the linear back projection algorithm (LBP) [11], the Tikhonov regularization method [12], the Landweber iteration method [13], the conjugate gradient method (CG) [14,15], the neural network algorithm [16] and so on. The LBP algorithm is simple and has fast reconstruction speed. Due to the relatively poor image quality, the LBP is only a qualitative algorithm. The Tikhonov regularization method is an effective method to solve the inverse problems, in which the regularization parameters have a great impact on image quality, but the selection of these parameters generally adopts the empiric values and has no enforceable rules. The Landweber iteration algorithm has in recent years been widely adopted. However, it is only the steepest descent algorithm from the viewpoint of numerical optimization, and the rate of

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convergence is relatively slow. When the coefficient matrix is symmetric positive definite, the CG algorithm has a short imaging time and fast convergence, but the CG has a bad performance on the complex flow patterns. For ECT image reconstruction, the neural network algorithm in essence is a pattern recognition method, and the successful application of the method completely depends on the rational network structure and training samples. However, it is difficult to obtain complete training samples owing to the randomness and complexity of the multiphase flow mid-stream change. And there are some difficulties in determining the network structure in the actual application.

Compressed sensing (CS) is a mathematical framework with several powerful theorems that provide insight into how a high resolution image can be inferred from a relatively small number of measurements using sophisticated computational methods [17–19]. Recently, CS has witnessed an increased high demand for fast, efficient and in-expensive signal processing algorithms, applications and devices [20,21]. Besides, the CS is growing rapidly in application of the electron tomography (ET), such as magnetic resonance imaging (MRI) [22] and X-ray computed tomography [23]. ECT image reconstruction is to obtain the material distribution from small number of known capacitance measurements. Hence, ECT inverse problem also can be approached as a CS problem [24]. The alternating direction method of multiphier (ADMM) is a new and effective method to solve the convex optimization problem, especially in the area of CS [25]. So far, no study has not been found that a combination of ADMM and CS is used to solve ECT inverse problem.

In this paper, inspired by the mathematical framework of CS, the ECT data acquisition is regarded as a linear measurement process of permittivity distribution signals over a pipe section. Then we design a new measurement matrix and use L1 regularization to convert ECT inverse problem to a convex relaxation problem. Finally, a new fast alternating direction method of multipliers which contained linearized idea (FLADMM) is employed to solve the objective function. The simulation and experimental results show that the proposed method improves the accuracy and the quality of the reconstructed images.

2. ECT System and Its Mathematical Model

2.1. Structure of ECT system

ECT system mainly consists of three parts: capacitive sensor, data acquisition and signal process, and image reconstruction, as shown in Fig. 1. Pairs of metal electrode plates are mounted uniformly around the outside of an insulted pipe and shielding cover. Fig. 2 shows the layout of ECT sensors. In Fig. 2, $R1$ is the pipe diameter; $R2$ is the distance between the center of pipeline and plate; $R3$ is the distance between the center of pipeline and the shield cover; and θ is the plate angle. The basic principle of ECT is to use the multi-phase flow media with different dielectric constant to obtain capacitance value of each pair of electrodes installed in insulated pipeline outer wall as the capacitance sensor. The capacitance values which reflect the distribution of dielectric constant across the pipeline is used to retrieve the two-phase flow concentration distribution map on the pipeline cross section by the computer. Moreover, with some certain image reconstruction algorithms, we can use the values to restore the physical phase image in the pipeline, namely intuitive access to distribution information of two-phase flow.

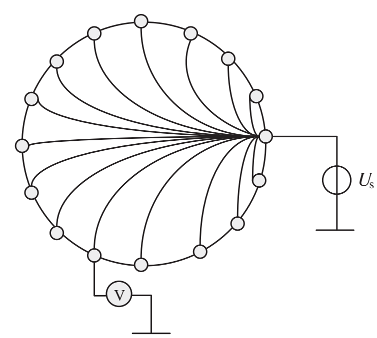

Fig. 3. Measurement model of ECT system.

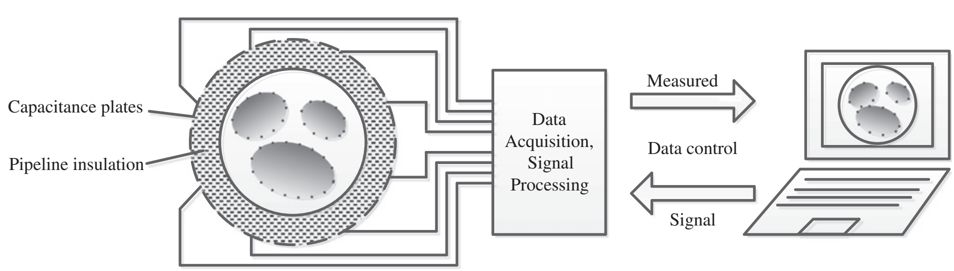

Fig. 1. Principles of ECT system.

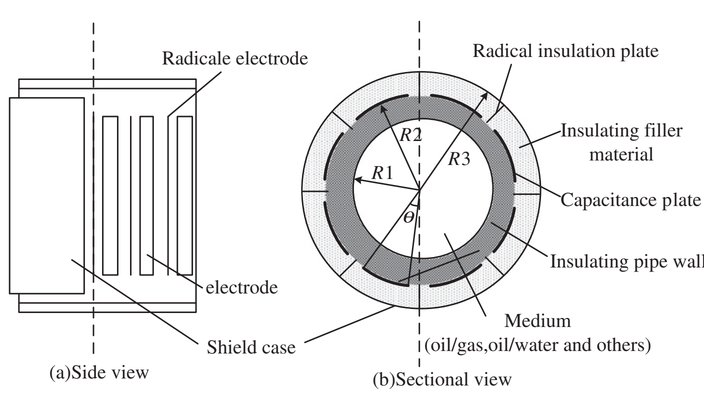

Fig. 2. Layout of ECT sensors.