ISSN : 1226-7244 (Print)
ISSN : 2288-243X (Online)
논문번호 24-02-10
j.inst.Korean.electr.electron.eng.Vol.28,No.2,187~198,June 2024
https://doi.org/10.7471/ikeee.2024.28.2.187
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Cuckoo search optimization algorithm for boundary estimation problems in electrical impedance tomography

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Abstract

Estimating the phase boundary in two-phase flow is crucial for designing and optimizing industrial processes. Electrical impedance tomography (EIT) is a promising technique for imaging phase distribution in such flows. This paper proposes using a cuckoo search (CS) optimization algorithm to estimate the phase boundary with EIT. The boundary is parameterized using the Fourier series, and the coefficients are determined by the CS algorithm. The CS algorithm iteratively seeks the phase boundary configuration by minimizing a cost function. Computer simulations and phantom experiments demonstrate the effectiveness of this method in estimating phase boundaries in two-phase flow.

Key words : Cuckoo search algorithm, electrical impedance tomography, Lévy flight mechanism, phase boundary estimation, two phase flow

Ⅰ. Introduction

Two phase flow occurs in various natural and industrial flow processes such as power generation plants, natural gas pumping and chemical engineering [1-2]. Phase boundary estimation in two phase flow systems is essential to optimize and monitor the industrial process. There are various methods to monitor the two phase flow but most commonly used methods are gamma densitometry [3], ultrasonic imaging [4] and nuclear magnetic resonance imaging [5] are used to visualize the flow processes.

Electrical impedance tomography (EIT) is promising imaging technique was employed to monitor the two phase flow, because it has many advantages such as low cost, non invasive and good temporal resolution over other tomography imaging methods [6]. The EIT imaging method can reconstruct the phase distribution of two-phase flow by applying the sinusoidal electrical currents through the electrodes placed on the boundary of the two-phase flow domain and collecting the corresponding voltage measurements [6-8].

EIT involves reconstructing internal resistivity or conductivity from measured voltages on electrodes. In two-phase flows, such as liquid-vapor mixtures, known conductivity values allow transforming the problem into boundary estimation, identifying the phase boundary's location and size [9-10]. The boundary can be closed or open, based on

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※ Acknowledgment
This research was supported by the 2024 scientific promotion program funded by Jeju National University
Manuscript received Jun. 13, 2024; revised Jun. 19, 2024; accepted Jun. 22, 2024.

topology. Closed boundary estimation is used when region boundaries are enclosed, like air bubbles forming under low pressure [9-10]. Open boundary estimation is applied in scenarios like petroleum extraction, where it's crucial to monitor the boundary between immiscible liquids, such as water and crude oil, especially when the pipeline isn't fully filled [11-14].

In EIT, shape parameterization employs mathematical models to precisely define internal boundaries, enhancing image reconstruction accuracy by improving spatial resolution. Shape representation techniques include using ellipses and circles for simple shapes, polygonal approximation for complex boundaries [15], B-splines for smooth and flexible curves [16], and Fourier descriptors for compactly representing intricate shapes with sinusoidal functions [17-20]. These methods improve ERT's precision and efficiency, making them essential for medical imaging, industrial process monitoring, and geophysical exploration applications.

Shape based image reconstruction for multiphase systems has recently attracted considerable attention. Techniques such as the traditional level set method (TLS) have been applied successfully in electrical tomography areas [21]. Furthermore, methods like parametric level set method (PLS) [22] and B-spline level set (BLS) [16] have also shown their effectiveness in EIT. These shape based approaches are referred as implicit shape reconstruction as they define phase boundary interface implicitly. Also, there are explicit methods where the boundary shape is represented as a collection of simple geometric operations that can vary the position, size and orientation [23-24]. Voids in the industrial process applications involving two phase flows take shape of elliptic or circular therefore Fourier shaped approach to parameterize the boundary can be used.

EIT inverse problem is generally solved using iterative methods such as modified Newton Raphson method involve computation of Jacobian which is computational cumbersome and also its performance is heavily dependent on the choice of initial guess and is not robust to measurement noise. Metahuristic methods which are Jacobian free and which problem global optimal solution can be an alternate method of solving the EIT inverse problem. New metaheuristic techniques to solve the optimization problem in EIT such as the particle swarm optimization (PSO) technique was used in EIT to estimate elliptical boundary [25]. Ribeiro et al [26] presented genetic algorithms for EIT reconstruction. Khambampati et al [27] used simplex methods for twophase flow estimation using EIT and Sharma et al [28-29] applied gravitational search algorithm (GSA) and hybrid PSO based GSA to estimate the boundary using EIT.

Here in this paper, we propose EIT inverse solver based cuckoo search (CS) optimization algorithm to estimate phase boundary. The CS optimization technique works based on the brood parasitic behavior of cuckoo birds with the Lévy flight mechanism of fruit flies [30-31]. CS optimization was formulated by yang and Debin [32]. Cuckoo bird slay eggs in other host bird's nest. Each egg in a host nest indicates a solution and a cuckoo bird egg in the host nest indicates a potentially better solution. A group of random solutions is generated based on the cuckoo bird habitat. The main aim of the CS optimization algorithm is to find new and better solutions to replace the weak solution in the host nest [33-34].

In this paper, we proposed a cuckoo search optimization algorithm to reconstruct the phase boundary in two phase flow system using EIT. Boundary of void or bubble in two phase flow is parameterized using the truncated Fourier series and the Fourier coefficients which describe the location and shape are estimated by the cuckoo search algorithm. We performed numerical simulations with real and noise measurements and phantom experiments to evaluate the performance of the proposed optimization algorithm and compared with reconstruction of the conventional commonly used modified Newton-Raphson method. The results show that the proposed cuckoo serach algorithm is able to estimate the shape and location of void in the pipe with good accuracy.

II. Mathmatical formulation of electrical impedance tomography

Reconstruction of the phase boundary of two phase flow in EIT can be obtained by solving the forward problem and the inverse problem. In EIT forward problem, the boundary voltages on electrodes can be calculated with the given injected currents and resistivity distribution of object inside the cylindrical domain. And in EIT inverse problem, the resistivity distribution of object is estimated using measured boundary potentials and applied electrical currents. In order to estimate the phase boundary in two phase flow, Electrical currents are applied through the boundary electrodes which are attached around the boundary of the cylindrical shaped phantom, electrical resistivity distribution within in cylindrical domain and measure the resulting voltages by the Maxwell equations given below [6].

$$\nabla \cdot \left(\frac{1}{\rho} \nabla u \right) = 0 \quad (1)$$

The complete electrode model (CEM) is used to represent the boundary conditions for injecting electrical currents and measure corresponding boundary potentials. The boundary conditions of complete electrode model are followed by [6-7]

$$u + z_l \sigma \frac{\partial u}{\partial n} = U_l, \ (x,y) \in e_l, \ l = 1,2,\ldots,L \quad (2)$$

$$\int_{e_l} \sigma \frac{\partial u}{\partial n} dS = I_l, \ (x,y) \in e_l, \ l = 1,2,\ldots L \quad (3)$$

$$\sigma \frac{\partial u}{\partial n} = 0, \ (x,y) \in \partial \Omega \setminus \bigcup_{l=1}^{L} e_l \quad (4)$$

Here is the applied current into the electrode, is the number of electrodes on the cylindrical shaped phantom, is the measured electrical potentials on the surface electrode and is the contact impedance between electrode and surface of the cylindrical boundary. Then the Kirchhoff's rules on the measured boundary potentials and the applied currents should guarantee the existence and uniqueness of the solution.

$$\sum_{l=1}^{L} I_l = 0, \ \sum_{l=1}^{L} U_l = 0 \quad (5)$$

III. Inverse problem and representation of phase boundary

In EIT inverse problem, the resistivity distribution of circular objects in cylindrical domain is estimated using measured boundary potentials and applied electrical currents. In this study, estimation of the phase boundary problem is treated as the inverse problem. The Boundary of the cylindrical domain is assumed. Boundary of phase in cylindrical domain is approximated using the Fourier series expansion approach [17-20], that is,

$$C_l(s) = \begin{pmatrix} x_l(s) \\ y_l(s) \end{pmatrix} = \sum_{n=1}^{N_\theta} \begin{pmatrix} \gamma_n^{x_l} \theta_n^x(s) \\ \gamma_n^{y_l} \theta_n^y(s) \end{pmatrix} \quad (6)$$

where the boundary of the l^{th} phase is, $C_l(s)(l = 1,2,\ldots,S)$, S represents the number of the phase boundaries in the cylindrical domain, $\theta_n(s)$ are periodic and differentiable basis functions and N_θ represents the number of basis functions. In this study, the phase boundaries are expressed as Fourier expansion in two-dimensional coordinates with respect to the curve parameter *s*, i.e, we use following the differentiable basis functions of the form

$$\theta_1^\alpha(s) = 1 \quad (7)$$

$$\theta_n^x(s) = \sin\left(2\pi \frac{n}{2} s\right), n = 2,4,6,\ldots N_\theta - 1 \quad (8)$$

$$\theta_n^y(s) = \cos\left(2\pi\frac{(n-1)}{2}s\right), n = 1,3,5,....N_\theta \quad (9)$$

where $s\epsilon[0,1]$ and α denotes either x or y. Furthermore, using Eq. (6), the phase boundaries are identified with the vector γ of the shape coefficients, that is,

$$\gamma = \left(\gamma_1^{x_1}.....\gamma_{N_\theta}^{x_1}, \gamma_1^{y_1}.....\gamma_{N_\theta}^{y_1}, ...\gamma_1^{x_s}.....\gamma_{N_\theta}^{x_s}, \gamma_1^{y_s}.....\gamma_{N_\theta}^{y_s}\right) \quad (10)$$

where $\gamma \epsilon R^{2SN_\theta}$. Then the cuckoo search optimization algorithm is applied to estimate the Fourier coefficients.

Ⅳ. Phase boundary estimation by Cuckoo search algorithm

A cuckoo search optimization algorithm is a meta-heuristic algorithm based on the brood parasitic behavior of female cuckoo birds [33]. These cuckoo species lay eggs in other host bird's nest with amazing abilities like selecting the recently spawned nests and removing existing eggs that increase the hatching probability of their eggs. The host bird takes care of the eggs presuming that the eggs are its own. However, some of host birds are able to identify with this parasitic behavior of Cuckoos, and throw out the discovered alien eggs or build their new nests in new locations. The cuckoo breeding analogy is used for developing a new designed optimization algorithm.

Each egg in a host nest indicates a solution and a cuckoo bird egg in the host nest indicates a potentially better solution. A group of random solutions is generated based on the cuckoo bird habitat. The main aim of the CS optimization algorithm is to find new and better solutions to replace weak solution in host nest. The algorithm works on the basis of following three assumptions [35]:

1. At a time, each cuckoo lay only one egg in the randomly chosen host nest;

2. The best host nests with high quality of cuckoo eggs (good solutions) will carry forward to the next generation;

3. The number of host nests is fixed and a host bird can discover an alien egg with the probability $Pa \in [0, 1]$. In this case, the host bird either throws the egg or destroys the nest completely and builds up a new nest somewhere else.

Now, the next step is to use the cuckoo search optimization algorithm to estimate the Fourier coefficients which minimizes the EIT Objective function. The objective function of EIT, which is the error between the boundary voltages on the surface electrodes and calculated potentials is then defined as

$$\Phi(\gamma_k) = \frac{1}{2}(U(\gamma_k) - U)^T\ (U(\gamma_k) - U) \quad (11)$$

where $U(\gamma_K)$ is the boundary voltages obtained through FEM in the iteration k and U is the measured voltage.

The new solution γ_{k+1} is produced based on the current solution with Lévy flights

$$\gamma_{k+1} = \gamma_k + \alpha^* S^* (\gamma_k - \gamma_k^{best})^* r \quad (12)$$

where γ_k is the current solution, α is the step size $\alpha > 0$, (considered as α = 0.01), r is a random number and γ_k^{best} is the best solution so far and Lévy flights by Mantegna's algorithm then the step length is calculated by [35]

$$S = \upsilon / |\nu|^{1/\beta} \quad (13)$$

where β is a within the interval [1, 2] (considered as β=1.5), υ and ν are from normal distribution is given by:

$$\upsilon \sim N(0,\delta_\upsilon^2),\ \nu \sim N(0,\delta_\nu^2) \quad (14)$$

$$\delta_\upsilon = \left\{\frac{\Gamma(1+\beta)^* \sin(\Pi\beta/2)}{\Gamma[(1+\beta)/2]^* \beta^* 2^{(\beta-1)/2}}\right\}, \delta_\upsilon = 1 \quad (15)$$

Applying the cuckoo search optimization algorithm to EIT for phase boundary estimation, we have to formulate the objective function to get the best fitness's at each iteration.

V. NUMERICAL SIMULATION RESULTS

To evaluate the performance of a cuckoo search optimization algorithm, Numerical simulations were performed for phase boundary estimation in cylindrical domain. Finite element mesh of 4 cm radius, 2793 triangular elements and 1497 nodes is employed to solve the EIT forward problem. Opposite current patterns are used for current injection through the 32 electrodes that are located on the boundary of cylindrical domain. Two numerical simulation scenarios were considered with a cylindrical domain that consists of circular and elliptical targets. Here it is assumed that the target with conductivity ($10x10^{-10}$ S/cm) located at the center of the cylindrical shaped domain with conductivity ($3.3x10^{-3}$ S/cm). The contact impedance between electrodes and outer surface of the domain is set to be 0.005. To represent the circular and elliptical targets, 6 Fourier coefficients were used. The Fitness function of cuckoo search is set to $1x10^5$ and Regularization parameter for modified Newton-Raphson (mNR) method set to $1x10^{-3}$.

The simulation results of case1 with phase boundary estimation considering circular shaped void using the cuckoo search algorithm and mNR after 10 iterations are shown in figure 1 and figure 2, respectively. In addition, 2% of relative measurement noise is added to the generated voltage measurements to make more realistic simulations. The true circular bubble target (red line) is located at the center of the cylindrical fluid domain while the estimated bubble target (blue dashed & green dotted targets) by the cuckoo search and mNR method are shown in figure 1 and magenta solid line represents an initial guess which is assumed for

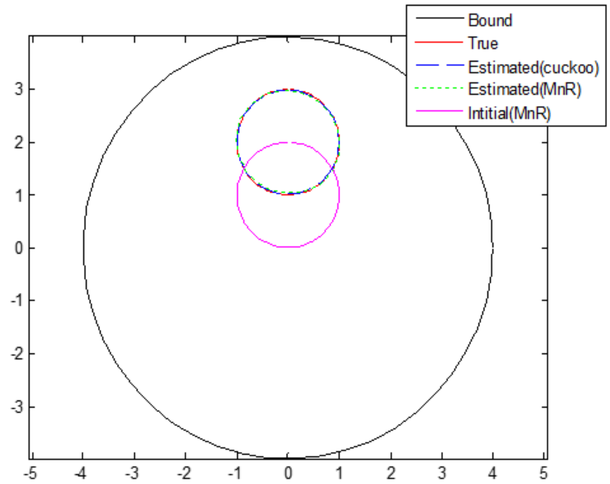

Fig. 1. Numerical results for phase boundary in case 1 with 0% relative measurement noise: red circle in a cylindrical domain represents the true phase boundary, blue dash line circular target represents the estimated boundary by cuckoo search and green dotted line circular target represents the estimated boundary by mNR.

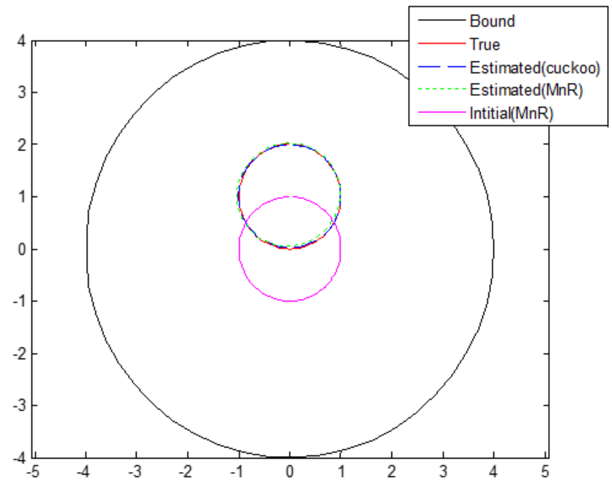

Fig. 2. Numerical results for phase boundary in case 1 with 2% relative measurement noise: red circle in a cylindrical domain represents the true phase boundary, blue dashed line circular target represents the estimated boundary by cuckoo search and green dotted line circular target represents the estimated boundary by mNR

mNR. Figure 2 is the true circular target boundary and estimated boundary with both CS and mNR methods. The reconstruction results show that the boundary estimation with CS method is better than the modified Newton-Raphson method even using very close initial guess. Both the location of void as well as the shape are reconstructed with good accuracy. Comparison of RMSE values for Fourier coefficients in both methods are evaluated and are summarized in table 1. Estimation error (RMSE) of the cuckoo search method shows significantly lesser than the mNR method.

In case 2 simulation results for elliptical target estimation with 2% relative measurement noise using CS and mNR methods are shown in figure (3 & 4). Figure 3 is the true elliptical phase boundary in cylindrical fluid domain and estimated target boundary with two methods. The true target in the fluid domain considering two phase flow and reconstructed images of CS and mNR methods are shown in Figure 4.

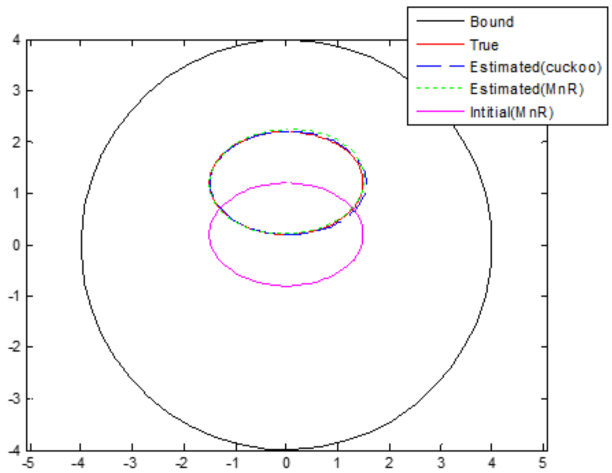

Fig. 3. Numerical results for phase boundary in case 2 with 0% relative measurement noise: red ellipse in a cylindrical domain represents true phase boundary, blue dashed line elliptical target represents the estimated boundary by cuckoo search and green dotted line elliptical target represents the estimated boundary by mNR.

As observed from reconstructed results in figure 3 and figure 4, it can be said that elliptical target estimation of CS method more accurate than the mNR method, even though using very closed initial guess.

The RMSE for Fourier coefficients from the both estimation techniques are compared in table 1. RMSE for Fourier coefficients is reduced significantly in CS method when compared to mNR method.

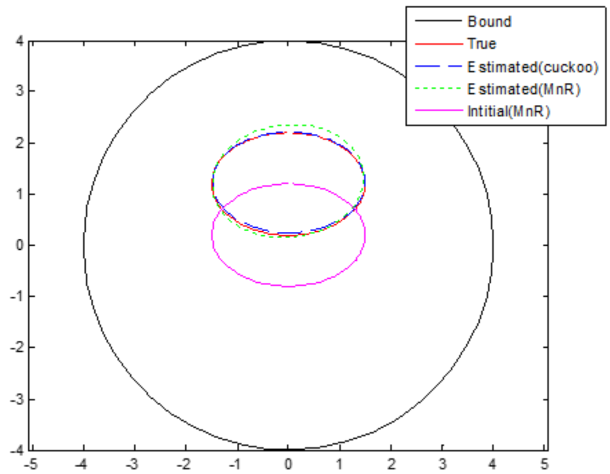

Fig. 4. Numerical results for phase boundary in case 2 with 2% relative measurement noise: red ellipse in a cylindrical domain represents true phase boundary, blue dashed line elliptical target represents the estimated boundary by cuckoo search and green dotted line elliptical target represents the estimated boundary by mNR.

Table 1. Comparison of RMSE for Fourier coefficients by mNR and Cuckoo search algorithm.

Method	Simulation case 1		Simulation case 2	
	0% relative noise	2% relative noise	0% relative noise	2% relative noise
mNR method	0.0607	0.12027	0.0254	0.0623
Cuckoo search	0.0042	0.0117	0.0177	0.0162

Ⅵ. Phase boundary estimation based on phantom experiment

The experiments were carried out from the EIT experimental system developed by Jeju national university research group. EIT experimental system consists of cylindrical shaped phantom with 32 electrodes, PC, an electrode switching module, a data acquisition system and an LCR meter. cylindrical shaped phantom is filled with saline solution that has conductivity of approximately 3.3×10^{-3}S/cm. Five experimental scenarios were considered with a cylindrical domain that consists of circular target at different locations. The Fitness function of cuckoo search is set to 1×10^{5} and Regularization parameter for modified Newton-Raphson (mNR) method set to1×10^{-3}.

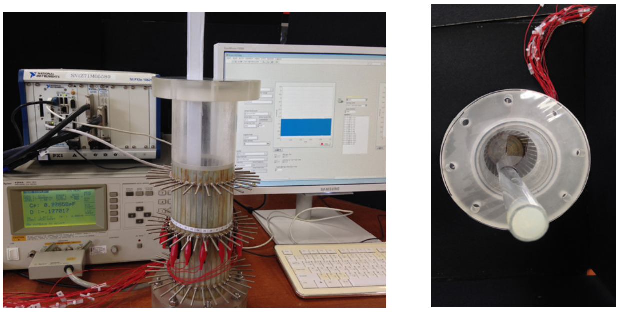

Fig. 5. Experimental setup used for phase boundary estimation in two phase flow imaging. (a) EIT experiment setup (b) phantom and plastic rod used as target to be visualized as voids.

Total five experimental cases are studied for phase boundary estimation. Case 1 is the situation where void or bubble is located in the east side towards the right side of phantom. The phase boundary results for case 1 are shown in figure 6. The true location of void is represented by red solid line while the estimated phase boundary using CS is shown using solid blue line and the estimated result with mNR method after 10 iterations is shown using green dotted line. A very close initial guess is used in obtaining the final solution of mNR. It is noticed that void location is estimated with good accuracy by CS and mNR however the size is slightly over estimated as compared to the true size. Estimated Fourier coefficients are compared by computing the RMSE and is shown in Table 2. RMSE of estimated Fourier coefficients with CS method for case 1 is 0.1025 where with mNR it is 0.1422 which suggests improved performance of CS over the traditional mNR for phase boundary estimation.

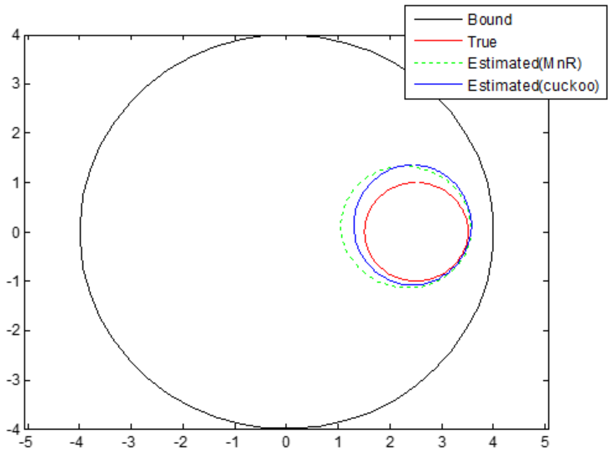

Fig. 6. Experimental results for phase boundary estimation in case 1 with void located at east side of phantom: red solid line in the domain represents the true phase boundary, blue solid line and green dashed line represents the estimated boundary by cuckoo search and mNR, respectively.

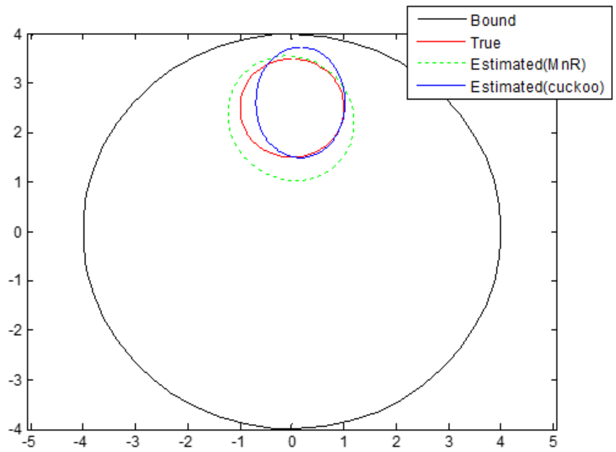

Fig. 7. Experimental results for phase boundary estimation in case 2 with void located at north top side of phantom: red solid line in the domain represents the true phase boundary, blue solid line and green dashed line represents the estimated boundary by cuckoo search and mNR, respectively.

In Case 2, the void is located at the top north side of the phantom. Figure 7 shows the boundary estimation results using the CS algorithm and the mNR method. The CS algorithm provides a more accurate estimation of the void's location compared to the mNR method, which tends to overestimate the void's size. The root mean square error (RMSE) of the Fourier coefficients for Case 2 is

0.1394 using the mNR method and 0.0946 using the CS method, indicating superior performance of the CS algorithm in boundary estimation.

In case 3, we have the void located in the west direction of the phantom and the estimation results for case 3 are shown in figure 8. It is noticed that the proposed CS method is able to estimate the true location of the target and also estimated size and shape is close to the true size. In mNR we can notice there is slight offset with regard to the location of void and also the void size is estimated bigger as compared to true size. The computed RMSE of Fourier coefficients for case 3 is 0.1107 for CS method and 0.1290 with mNR.

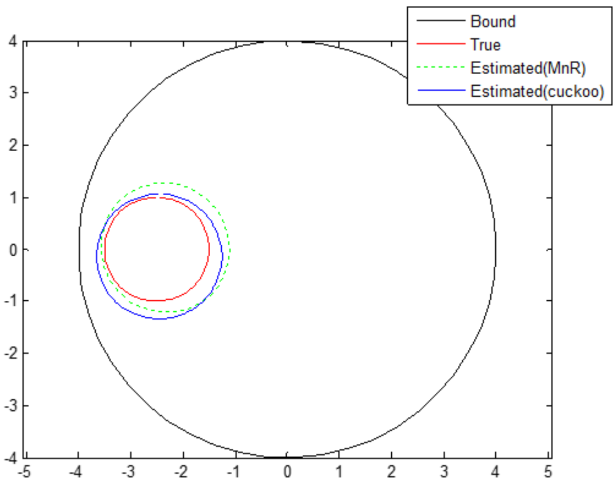

Fig. 8. Experimental results for phase boundary estimation in case 3 with void located at west left side of phantom: red solid line in the domain represents the true phase boundary, blue solid line and green dashed line represents the estimated boundary by cuckoo search and mNR, respectively.

In Case 4, the void is located in the bottom south part of the phantom, and the estimated phase boundaries are shown in Figure 9. Both the CS and the mNR method accurately estimate the circular shape of the void, although both methods overestimate its size. The mNR method tends to estimate a larger void size compared to the CS algorithm. The root mean square error (RMSE) of the Fourier coefficients for Case 4 is 0.1007 for the CS method, which is lower than the 0.1347 obtained with the mNR method, indicating better performance by the CS algorithm.

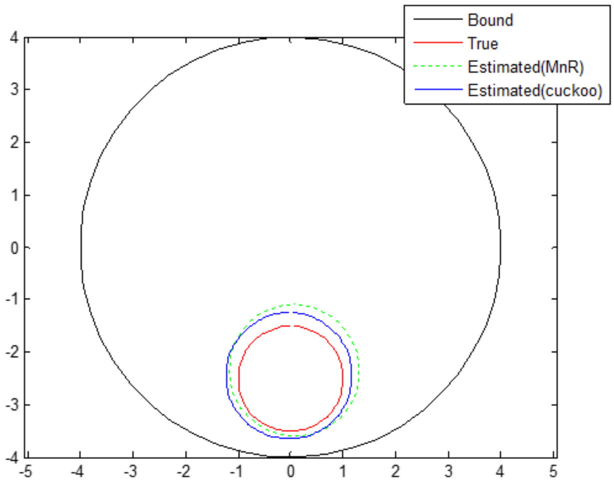

Fig. 9. Experimental results for phase boundary estimation in case 4 with void located at south down side of phantom: red solid line in the domain represents the true phase boundary, blue solid line and green dashed line represents the estimated boundary by cuckoo search and mNR, respectively.

In case 5, we test the performance of proposed method when the void is located at the center portion of the phantom. In the center region the sensitivity is less as compared to the situation when the void is close to the boundary. The estimation result for case 5 is shown in figure 10. It is seen from figure 10 that CS has estimated the void shape and location with better accuracy. The mNR has estimated the void shape as ellipse and void size much bigger than the true size. The RMSE of Fourier coefficients for case 5 are computed and shown in Table 2. The RMSE of Fourier coefficients for estimated result of CS in figure 10 has a value of 0.2147 while mNR has higher value of 0.3735. It can be noted that higher RMSE values are seen in case 5 when the void is at the center as compared to other four cases where the void is located close to the phantom boundary as the sensitivity is less at the center region.

It is noted that in all the five experimental cases the proposed CS method estimated the void location and boundary shape with good accuracy as compared to the traditional mNR method whose result is very much dependent on the choice of initial guess and measurement noise.

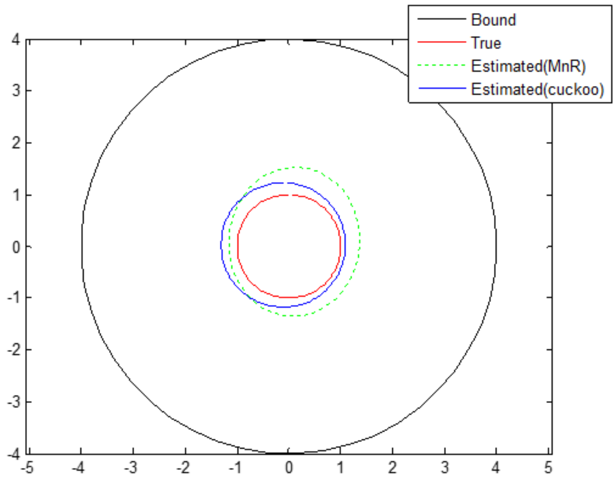

Fig. 10. Experimental results for phase boundary estimation in case 5 with void located at center of phantom: red circle in a cylindrical domain represents the true phase boundary, blue dashed line target represents the estimated boundary by cuckoo search and green dotted line target represents the estimated boundary by mNR.

Table 2. Comparison of RMSE for Fourier coefficients by mNR and Cuckoo search algorithm with different experimental scenarios.

Method	Experimental case 1	Experimental case 2	Experimental case 3	Experimental case 4	Experimental case 5
mNR method	0.1422	0.1394	0.1290	0.1347	0.3735
Cuckoo search	0.1025	0.0946	0.1107	0.1007	0.2147

Ⅶ. Conclusion

This paper proposes a Cuckoo Search (CS) optimization algorithm to estimate the phase boundary in a two-phase flow system using Electrical Impedance Tomography (EIT). Voids or bubbles in the flow are assumed to have smooth boundaries and the phase boundary are parameterized using truncated Fourier series. Inspired by the brood parasitic behavior of female cuckoo birds, the CS algorithm is Jacobian-free and excels in estimating phase boundaries due to its superior global convergence rate and local search capability. Numerical simulations were conducted to reconstruct phase boundaries in a cylindrical fluid domain with 0% and 2% measurement noise, covering circular and elliptical targets. Additionally, five phantom experiments were performed with bubbles appearing at various locations within the cylindrical domain. The estimated phase boundary images and root mean square error (RMSE) for Fourier coefficients obtained with the CS algorithm were compared to those of modified Newton-Raphson (mNR) method. Results from both numerical and phantom experiments demonstrate that the proposed CS algorithm provides more accurate phase boundary estimations than the traditionally used mNR method.

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