Multi-Domain Level-set Method for Design Optimization of Primary and Secondary Cores in Induction Heating Roll

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Level-set method has an advantage compared to other optimization methods of being able to derive a more feasible shape. However, the drawback of the method is that its result occasionally falls into a local optimal solution when solving a complicated problem. To overcome this drawback, we propose the multi-domain level-set method which divides an entire design domain into multiple domains and individually normalizes the velocity vector based on design sensitivity in each domain. This leads to an effective optimization by preventing the underestimation of a relatively small velocity vector which improves an objective function. To confirm the validity of our proposed method, we carry out shape optimization of primary and secondary cores in an induction heating roll as a numerical example. Consequently, our proposed level-set method successfully achieves better shapes than those by the conventional one.

***Index Terms*— Design optimization, electromagnetic induction, level set, magnetic fields, optimization methods.**

I. Introduction

Heating rolls are applied to various kinds of manufacturing processes in textile, non-woven, paper, printing, and film industries. Induction heating has become increasing popular for heat generation because of its fast response to changes in temperature setting. Fig. 1 shows the 3D structure of an induction heating roll. The improvements of various performance aspects from induction heating machinery are as follows: Temperature uniformity is improved by inserting heat pipes with high thermal conductivity [1]. The amplitude and the frequency of the input current and the position and the copper volume of coils are optimized for ameliorating heating efficiency [2]-[3]. In addition, in our previous research, we implemented the shape optimization of primary core which has great influence on the heating performance by level-set method [4].

To further improve the heating performance, it is effective to expand the scope of the design domain. Therefore, in this paper, we carry out the shape optimization of the secondary core as well as the primary core, i.e., simultaneous shape optimization over multi-domain. In the optimization, we adopt the level-set method which is an attractive design tool for actual devices. There are few reports on the optimization which considers multi-domain by level-set method.

Level-set method represents material boundaries by utilizing level-set function and performs optimization with advection in accordance with design sensitivity [5]-[6]. Since the gray scale width is restricted to the vicinity of the material boundaries, the method has the advantage of obtaining a more feasible shape in comparison with other optimization methods. However, the shortcoming is that its result occasionally falls into a local optimal solution in the case of complicated problems. Therefore, in order to expand the search space, we propose a novel multi-domain level-set method which divides an entire design domain into multiple domains and individually normalizes the velocity vector based on the design sensitivity in each domain. This method is expected to prevent us from neglecting a relatively small velocity vector on the material boundaries which has a good effect on the enhancement of heating performance. To verify our proposed method, we conduct magnetostatic shape optimization of primary and secondary cores in induction heating roll. As a result, the objective function value by our proposed level-set method is better than that by the conventional one.

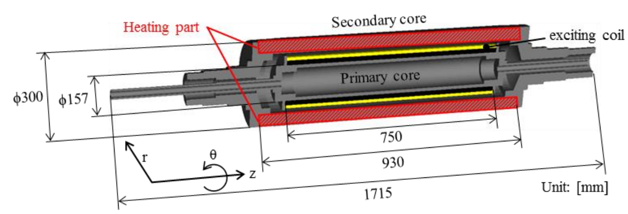

Fig. 1. 3D structure of an induction heating roll (half region).

II. Proposed Level-set Method

The update formula of level-set function with forward Euler time integration described in [6] is given below (1).

$$\boldsymbol{\Phi}^{(k+1)} = \boldsymbol{\Phi}^{(k)} + \Delta t \boldsymbol{V_H}^{(k)} \tag{1}$$

where $\boldsymbol{\Phi}^{(k)}$ is the level-set functions at the kth iteration, Δt is the time step size, and $\boldsymbol{V_H}^{(k)}$ denotes the velocity vector of boundary advection at the kth iteration calculated by the design sensitivity. With regard to the time step size Δt, Courant-Friedrichs-Lewy (CFL) condition is often utilized for numerical stability.

$$\Delta t \le \frac{\Delta x_{\min}}{\left\| \boldsymbol{V_H}^{(k)} \right\|_\infty} \tag{2}$$

where $\Delta x_{\min}$ is the minimum edge of elements in the design domain and $\|\boldsymbol{V_H}^{(k)}\|_\infty$ is the maximum value of $\boldsymbol{V_H}^{(k)}$.

As described above, the transition width $\Delta t \boldsymbol{V_H}^{(k)}$ of the level-set function is determined through normalization by the maximum of the velocity vector, i.e., $|\boldsymbol{V_H}^{(k)}|_\infty$ in (2). The conventional level-set method normalizes the velocity vector in consideration of the entire design domain. On the other hand, our proposed level-set method divides an entire design domain into multiple domains and individually normalizes the velocity vector by using $|\boldsymbol{V_H}^{(k)}|_\infty$ in each domain.

III. Numerical Examples

A. Investigated Model

Fig. 2 shows the cross-section of the induction heating roll of the 2D linear magnetostatic shape optimization model. The design variable is the shape of silicon steel in the design domains. The purpose of optimization is to improve heating speed and temperature uniformity in the heating part in an eddy current field. In the magnetostatic model, as described in (3), we define the objective function as the magnetic energy in the edge of the heating part (target area Ω_t) for the reasons below. The magnetic flux passing through the target area Ω_t flows through the whole heating part and induces eddy current. The increase of the objective function value improves heating speed and temperature uniformity simultaneously.

$$\text{max.} \quad W = \int_{\Omega_t} \frac{1}{2} \nu B^2 dS \tag{3}$$

where ν is the magnetic reluctivity.

In addition, the area constraint (4) is built in the design domain Ω_{d1} so that the optimal shape Ω_{opt1} does not have larger area than the current shape Ω_{c1}. An area constraint in the design domain Ω_{d2} is not considered because the configuration of Ω_{d2} is the same as that of the current shape Ω_{c2}.

$$\text{s.t.} \quad G = S_{\Omega_{opt1}} - S_{\Omega_{c1}} \le 0 \quad \text{in } \Omega_{d1} \tag{4}$$

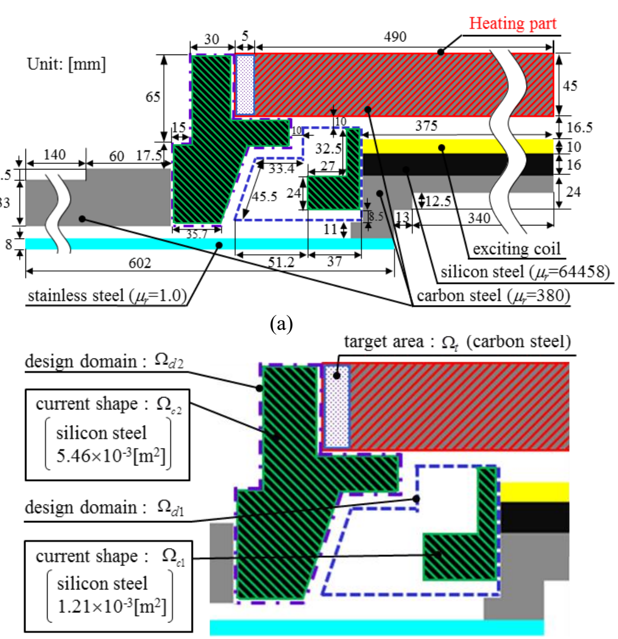

Fig. 2. Optimization model (1/4 region): (a) overall view, (b) enlarged view.

B. Optimization Results

The optimization problem mentioned in the previous section is solved by the conventional and the proposed methods. The conventional method regards domains Ω_{d1} and Ω_{d2} as one design domain and simultaneously carries out the shape optimization of the magnetic materials in both domains. The proposed method also simultaneously carries out the optimization in Ω_{d1} and Ω_{d2}. However, its optimization process is based on the velocity vector individually normalized in each domain. Fig. 3 shows the optimization results indicating essential frames of magnetic circuits.

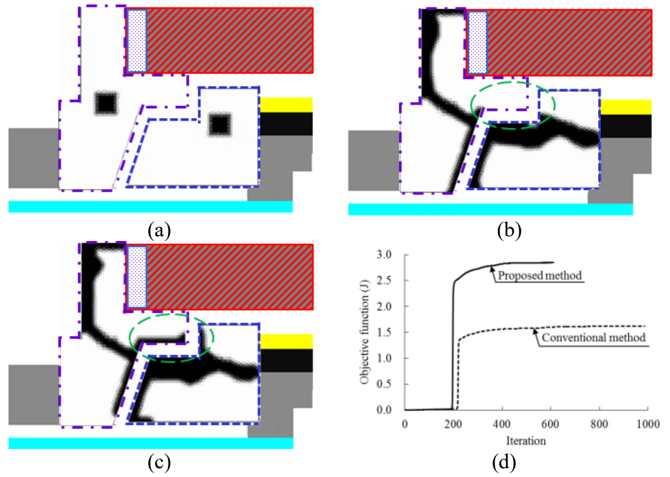

Fig. 3. Optimization results: (a) Initial shape, (b) Optimal shape by the conventional method, (c) Optimal shape by the proposed method, (d) Objective function values.

As shown in Fig. 3 (b) (c), there is difference between the obtained shapes of both methods, especially in the area surrounded with broken line. This indicates that the velocity vector around the area is underestimated in the conventional level-set method. Fig. 3 (d) shows that the proposed method obtains higher objective function values than that of the conventional level-set method. The objective function values ascend rapidly around the 200th iteration because the magnetic circuits reach the target domain. These results shown in Fig. 3 confirm the validity of the proposed method.

In the extended paper, we will make the final decision of a manufacturable core configuration in consideration of the essence of the optimization results. We will also apply the proposed method to the nonlinear magnetic problems and more numerical results will be reported to further demonstrate the validity of the proposed multi-domain level-set method.

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