Simultaneous Design Approach to Transient Electromagnetic and Thermal Problems Based on a Black-Box Modeling Concept

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***Abstract*—This paper proposes a simultaneous design approach for a transient electromagnetic and thermal problem of which the electromagnetic and thermal parameters are strongly coupled with each other. To effectively deal with the problem, the Kriging method based on a hyper-cubic local window is adopted as a black-box modeling technique. Exploiting the design sensitivity information extracted from the surrogate models for outputs of interest, the gradient-based optimization algorithm is used for obtaining an optimum. The proposed method is tested with a strongly coupled induction heating problem where the design goal is to achieve the desired temperature distribution on the surface of a metal workpiece in a given heating time.**

***Index Terms*— Electromagnetics, metamodeling, optimization, sensitivity analysis, thermal analysis.**

I. Introduction

Electromagnetic (EM) systems include subsequent thermal (TM) or mechanical phenomena. From the viewpoint of numerical analysis, such the systems fall under either a weakly coupled problem or a strongly coupled problem. Recently, several research works have been made to design the coupled problems [1], [2]. Most of them dealt with the weakly coupled problems by using the sensitivity-based optimization methods. However, engineers are often faced by difficulties in designing the strongly coupled and transient problems due to the following reasons: 1) there are few articles regarding this issue, 2) the sensitivity-based methods require very cumbersome works (e.g. construct the adjoint system or modify the source codes), 3) A engineer usually has no in-depth knowledge of all the areas of the multiphysics concerned.

To overcome the aforementioned difficulties, this paper proposes a simultaneous design approach to strongly coupled and transient EM-TM problems based on the black-box modeling which needs only input parameters and output performances. As a practical and efficient black-box modeling, a sampling-based sensitivity method consisting of the Kriging method and the hyper-cubic local window concept is introduced. The proposed method is applied to a transient induction heating design problem with two different electric conductivity conditions (i.e. constant conductivity and temperature-dependent conductivity). The results show that two optimal designs have quite different coil positions even though same objective and constraint functions are imposed.

II. Direct Design Approach

While the previous research works mostly suggest a sequential design approach to the coupled problems, this paper proposes the simultaneous design process without intervening in internal affairs of the coupled EM-TM simulator. Moreover, for enhanced computational efficiency, surrogate models based on a local window at the current design are utilized and their sensitivity values are exploited for gradient-based searching techniques.

A. Black-Box modeling

The scheme of the proposed method is illustrated in Fig. 1. The key point is to use the low-order black-box modeling technique [3]. That is, an approximate function $\hat{\mathbf{y}}$ based on the first-order basis functions for a real response $\mathbf{y}$ is generated not in the whole design space but only in a relatively small region with the center at the current design point. Consequently, such the local window concept leads to significant reduction of random sampling points. Meanwhile, it has been reported that the window concept yields sensitivity information with very high precision compared with other sensitivity-based methods [4]. The main features of the proposed method are summarized as: 1) acceptable computation cost, 2) no access to internal data of the simulator, 3) easy implementation even without in-depth knowledge of the coupled system, 4) program architecture suitable for parallel computing.

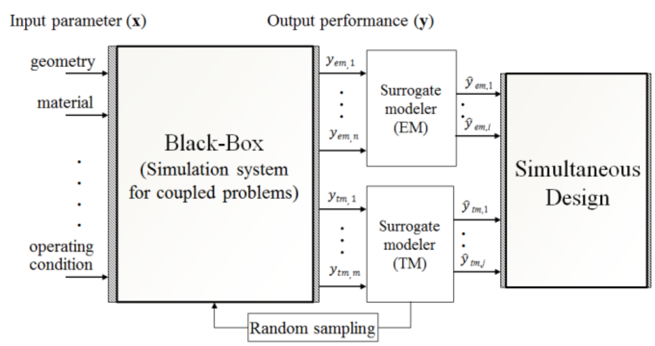


Fig. 1. Proposed design approach to coupled problems.

B. Sampling-based sensitivity equation

In the Kriging method, the goal is to estimate a response $\mathbf{y}=[y(\mathbf{x}_1),\cdots,y(\mathbf{x}_n)]^T$ with $y(\mathbf{x}_i)\in\mathbf{R}^1$ based on n sample points, $\mathbf{x}=[\mathbf{x}_1,\cdots,\mathbf{x}_n]^T$ with $\mathbf{x}_i\in\mathbf{R}^m$. The response consists of summation of two parts: mean structure of the response $\mathbf{F}\boldsymbol{\beta}$ and realization of the stochastic process $\mathbf{e}$ as

$$\mathbf{y}=\mathbf{F}\boldsymbol{\beta}+\mathbf{e} \quad (1)$$

where $\boldsymbol{\beta}$ is the vector of regression coefficient. Applying fairly routine mathematical processes such as the maximum likelihood estimator and the Lagrange multiplier, the prediction $\hat{y}$ of (1) which interpolates the n sample points around the point $\mathbf{x}_0$ of interest is expressed as

$$\hat{y}(\mathbf{x}_0) = \mathbf{f}_0^T \boldsymbol{\beta} + \mathbf{r}_0^T \mathbf{R}^{-1}(\mathbf{y} - \mathbf{F}\boldsymbol{\beta}) \qquad (2)$$

where $\mathbf{f}_0$ is the basis function vector at $\mathbf{x}_0$, $\mathbf{r}_0$ is the correlation vector between $\mathbf{x}_0$ and samples $\mathbf{x}$, and $\mathbf{R}$ is the symmetric correlation matrix. Finally, the derivative $\hat{y}'$ of the prediction model (2) at $\mathbf{x}_0$ is obtained as [4]

$$\hat{y}'(\mathbf{x}_0) = \mathbf{J}_\mathbf{f}^T \boldsymbol{\beta} + \mathbf{J}_r^T \mathbf{r}_0 \qquad (3)$$

where $\mathbf{J}_\mathbf{f}^T$ and $\mathbf{J}_r^T$ denote the Jacobian transformations of $\mathbf{f}_0$ and $\mathbf{r}_0$, respectively.

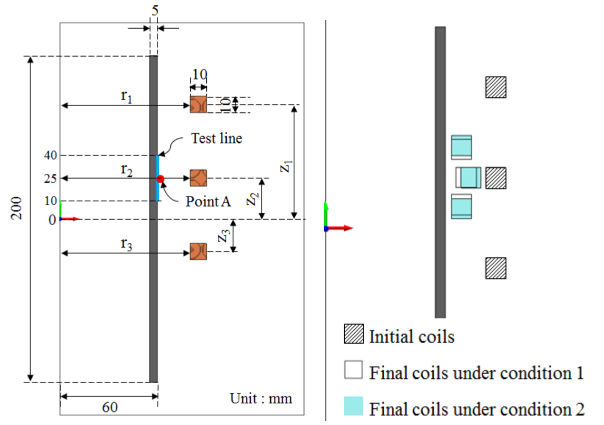
III. Results

The proposed method is applied to an exciting coil positioning problem of the induction heating system depicted in Fig. 2(a) where only half a model is presented owing to the axisymmetric condition. The workpiece is a non-ferromagnetic 304 stainless steel pipe. Its physical properties such as electrical conductivity, thermal conductivity, and heat capacity comply with [5]. The coils are excited by a sinusoidal current source with a frequency of 10 kHz and a r.m.s value of 1,800 A. To predict the performance of the heating system, a transient TM analysis tool, called ThermNet, is coupled with a time-harmonic EM analysis tool, called MagNet [6]. The design goal is to find a coil location for producing the desired temperature distribution on a part of the pipe surface at a final heating time of 15 seconds, while a coil inductance constraint is satisfied. The design problem is formulated as

$$\begin{aligned} &\text{minimize} \quad f(\mathbf{x}_0) = \sum_{i=1}^{np} (T_i - T_{i0})^2 \\ &\text{subject to} \quad L^L \le L_j \le L^U \qquad j = 1,2,3 \end{aligned} \qquad (4)$$

where $\mathbf{x}_0$ is the design vector consisting of 6 variables shown in Fig. 2(a), np is the number of the nodes on the test line, T_i is the temperature on the ith node with the target temperature T_{i0} of 1,000°C at the final time, and L_j denotes the jth coil inductance with the lower and the upper limits, L^L and L^U.

For investigating the validity of the proposed method and the effect of the electrical conductivity condition, the design problem was solved with two different conditions: The condition 1 has a constant conductivity value; and the condition 2 has temperature-dependent conductivity. The sequential quadratic programing technique was used for the constraint optimization problem of (4). Starting with the same initial coils, two different final coil positions were obtained as shown in Fig. 2(b). To achieve this, the condition 1 required 16 iterative designs and 127 black-box calls, and condition 2 needed 15 iterative designs and 137 black-box calls (refer to Fig. 1). For the three different coil positions, the temperature variations at the point A and the temperature distributions on the test line are compared in Figs. 3 and 4. It is observed that the conductivity condition for the EM-TM coupled design problem makes considerable effects on the final coil position and the thermal performances. Moreover, it is revealed that the proposed method requires relatively small design iterations to obtain an optimum even though the Latin hypercube random sampling technique is used. From the results, it is inferred that the method is very easy and effective approach to simultaneously dealing with EM and TM performances of the coupled transient design problem.



(a) schematic (b) coils

Fig. 2. Configuration of a design model and three different coil positions.

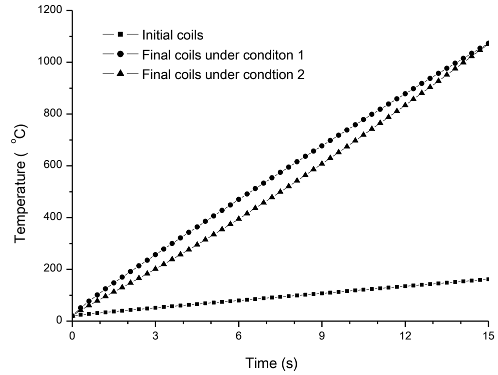


Fig. 3. Temperature variations versus time at the point A.

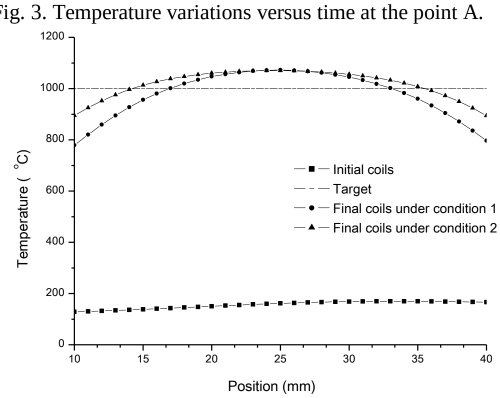


Fig. 4. Temperature distributions on the test line.

References

[1] I. Kwak, and S. Hahn, "Design sensitivity of transient electro-thermal problems for the specific temperature distribution," *IEEE Trans. on Magn.*, vol. 36, no. 4, pp. 1148-11152, 2000.

[2] S. Park and J. Yoo, "Structural optimization of a multi-physics problem considering thermal and magnetic effects," *IEEE Trans. on Magn.*, vol. 48, no. 11, pp. 3883-3886, 2012.

[3] V. Valdivia, et al., "Black-box modelling of three-phase voltage source inverters for system-level analysis," *IEEE Trans. on Ind. Electron.*, vol. 59, no. 9, pp. 3648-3662, 2012.

[4] I. Lee and K. Choi, "Sampling-based RBDO using the stochastic sensitivity analysis and dynamic Kriging method," *Struct. Multidisc. Optim.*, vol. 44, pp. 299-317, 2011.

[5] http://www.upmet.com/products/stainless-steel/304304l-ann/physica.

[6] *MagNet/ThermNet User's Manual*, Infolytica Corporation, Quebec, Canada, 2008.