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A MODIFIED INVERSE SCHEME FOR MAGNETIC MATERIAL CHARACTERIZATION OF AN ELECTROMAGNETIC DEVICE WITH MINIMAL INFLUENCE OF MULTIPLE GEOMETRICAL UNCERTAINTIES

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Abstract. The properties of the magnetic core materials inside electromagnetic devices can be retrieved by solving an electromagnetic inverse problem. In such inverse problems, the unknown parameters are recovered by interpreting well-chosen measurements using a forward numerical model. However, the modeling errors originating from the uncertainties of the geometrical parameter values often degrade the accuracy of the recovered values of the material parameters. In this paper, we propose an efficient inverse scheme for reducing the effect of multiple geometrical uncertainties. This deterministic technique adapts the objective function to be minimized with the sensitivity of the forward numerical model to the uncertain parameters. The proposed methodology is validated for the identification of the magnetic material parameters of a few electromagnetic devices, where the forward model exhibits multiple geometrical uncertainties. The numerical results show a large reduction of the recovery errors within an acceptable computational time.

Keywords: Inverse problem, magnetic material characteristics, multiple uncertainties.

INTRODUCTION

Soft magnetic materials are indispensable components in all electromagnetic devices (EMDs), such as rotating electrical machines. The knowledge of the magnetic material properties is inevitable for analyzing such applications. The magnetic material properties in the electromagnetic devices are classically identified by means of standard techniques. Measurements are then carried out on a separate sheet of the same material as the electromagnetic device by using an Epstein frame, single sheet tester or ring core measurements. However, this requires extra samples of the electrical steel sheet of which the electromagnetic device is manufactured, which are often unattainable. Moreover, the magnetic material characteristics may be altered during the construction of the electromagnetic device, e.g. due to the introduced cutting stresses. Therefore, in order to characterize the present magnetic properties, it is more accurate to identify the magnetic properties on the specific geometry of the EMD itself, which can be solved using a coupled experimental-numerical inverse approach [1]. This inverse approach iteratively minimizes the difference between the numerical model responses and the measurement quantities. However, numerical model responses are highly affected by the uncertainties in the geometrical model parameter values, e.g. the air gap thickness. Therefore, a deterministic technique, namely minimum path of the uncertainty (MPU), has been proposed for reducing the impact of the uncertain geometrical parameters on magnetic material identification of an EMD using an adaptive inverse algorithm [2]. Although this proposed inverse scheme showed a large modeling error reduction, it is a time consuming technique especially when dealing with multiple uncertainties. Therefore, we propose in this paper a significant modification of the MPU technique in order to accelerate the solution. The modified MPU approach is definitely computationally efficient for an inverse problem with multiple uncertainties.

METHODOLOGY

The behavior of a magnetic system can be represented by a mathematical model with a set of partial differential equations. This model is parameterized by the following model parameters: the *unknown* parameters $\mathbf{u} \in \Re^p$, the *uncertain* parameters $\mathbf{b} \in \Re^q$, and the precisely *known* parameters $\mathbf{d} \in \Re^x$. In case of noise-free measurements and correct modeling of the forward problem, the experimental observations of the magnetic system $\mathbf{W} \in \Re^K$ can be expressed as: $\mathbf{W} = \mathbf{\Phi}\left(\mathbf{u}^*, \mathbf{b}^*, \mathbf{d}\right)$, where $\mathbf{\Phi} \in \Re^K$ is the modeled response, and K is the total number of discrete experimental observations. $\mathbf{u}^*$ and $\mathbf{b}^*$ are the actual values of the *unknown* and *uncertain* model parameters, respectively.

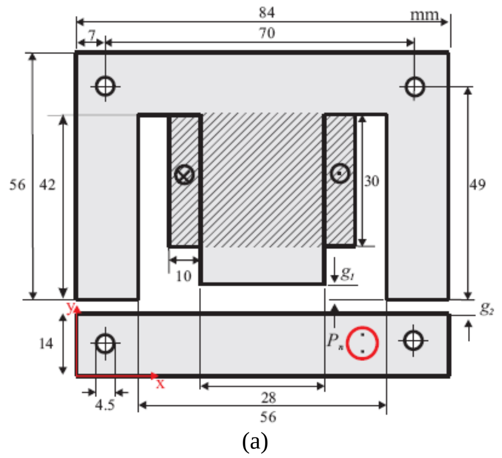
Generally, in order to estimate the *unknown* parameters $\mathbf{u}$, an inverse problem has to be solved by iteratively minimizing the sum of the quadratic *residuals* between the experimental and modeled observations. In other words, the functional: $OF_{Trad}(\mathbf{u}) = \left\|\mathbf{\Phi}(\mathbf{u}, \mathbf{b}, \mathbf{d}) - \mathbf{W}\right\|^2$ needs to be minimized: $\tilde{\mathbf{u}} = \mathbf{arg\,min}_{\mathbf{u}}\, OF_{Trad}(\mathbf{u})$, with

$\tilde{\mathbf{u}}$ being the recovered values of the *unknown* model parameters. Particularly, when $\mathbf{b}=\mathbf{b}^*$ is satisfied, then the inverse problem is capable of recovering, in noise-free case and with a perfect forward model, the actual unknown parameters, i.e. $\tilde{\mathbf{u}}=\mathbf{u}^*$. However, in practice, the knowledge of $\mathbf{b}$ is uncertain and the used value can differ from the actual value, which results in an error in the recovered parameters, i.e. $\tilde{\mathbf{u}}\neq\mathbf{u}^*$.

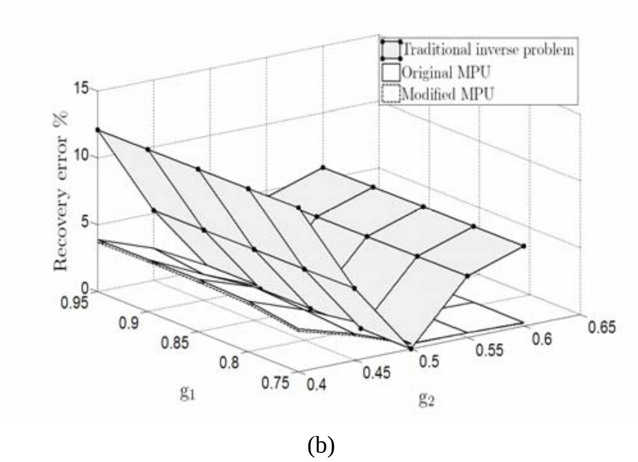
In [2], the authors have presented a deterministic technique in order to reduce the effect of the uncertain parameter **b** on the inverse problem solution. The proposed technique, namely minimum path of the uncertainty (MPU), adapts at each iteration step the objective function to be minimized with the sensitivity of the forward model with respect to the uncertain model parameters. Hence, the objective function becomes $OF_{MPU}(\mathbf{u})=\left\|\mathbf{\Phi}(\mathbf{u},\mathbf{b}^{\bullet},\mathbf{d})+\alpha(\partial\mathbf{\Phi}/\partial b_1)\big|_{b_1=b_1^{\bullet}}+\beta(\partial\mathbf{\Phi}/\partial b_2)\big|_{b_2=b_2^{\bullet}}+\cdots+\gamma(\partial\mathbf{\Phi}/\partial b_q)\big|_{b_q=b_q^{\bullet}}-\mathbf{W}\right\|^2$, where $\alpha,\beta,\gamma,\cdots$ are constants obtained by fitting two vectors $(\mathbf{\Phi}(\mathbf{u},\mathbf{b}^{\bullet},\mathbf{d})-\mathbf{W})$ and $(\partial\mathbf{\Phi}/\partial b_q)$. $b_q^{\bullet}$ is the assumed value of the uncertain model parameter used in the forward model, for more information see [2]. The main disadvantage of this method is its heavily computational burden, especially when dealing with multiple uncertainties. The computational time of the MPU is approximately (q+1) times the computational time of the traditional inverse problem. Therefore, in this paper, we modify the previous objective function by calculating the sensitivity of the forward model with respect to the uncertain model parameters *a priori* using a second order response surface method approximation. However, calculating the fitting constants is still done iteratively.

RESULTS AND DISCUSSION

Fig. 1-a shows the profile of the studied EI electromagnetic inductor. In this paper, we assume that the dimensions of the EI core inductor are precisely known, except for the values of the two air gap thicknesses g_1 and g_2, which are uncertain with the mean values of 0.85 mm and 0. 5 mm, respectively. The magnetizing *B-H* curve of the EI magnetic core material is characterized by $H/H_0=B/B_0\left(1+(B/B_0)^{(\nu-1)}\right)$, with parameters $\mathbf{u}=[H_0,B_0,\nu]$ to be identified. Fig. 1-b shows the recovery errors in the identified magnetic material properties of the EI core material when using the original and modified MPU technique compared to the traditional inverse approach. The recovery error values are calculated based on the deviation of the root mean squared values of the recovered *B-H* curves compared to the original *B-H* characteristics. It is clear from Fig. 1-b that the recovery error using the original and modified MPU technique is appreciably decreased compared to the traditional one. Moreover, it is worth mentioning that the computational time of the modified MPU technique is largely reduced compared to the original MPU formulation, i.e. approximately two times, in this specific case study. In fact, the proposed modified MPU becomes much more important in 'on-line' parameter identification problem, e.g. biomedical applications, because the computing time is of great importance in such problems.



(a)



(b)

Fig. 1: (a) Studied EI core inductor. (b) The recovery error values for the original and modified MPU technique compared to the traditional inverse approaches based on local magnetic induction measurements at P_n.

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