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Sensorless parameter estimation of electromagnetic transducer considering eddy currents

Toru Ikegame[a,*], Kentaro Takagi[a], Tsuyoshi Inoue[a], Ichiro Jikuya[b]

[a] Department of Mechanical Systems Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan
[b] Faculty of Electrical and Computer Engineering, Kanazawa University, Kakuma-machi, Kanazawa, 920-1192, Japan

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ABSTRACT

This paper presents a method of estimating the parameters of an electromagnetic transducer without sensors. The proposed method utilizes the measured admittance of the electromagnetic transducer, and therefore position, velocity, and/or acceleration sensors are not necessary in this framework. Novel impedance models are proposed based on the basic physical principles of electromagnetics; in particular, the effect of eddy currents has been included in these proposed models. The validity of the proposed estimation method and models was experimentally demonstrated by comparing the parameter estimation and vibration control capabilities of the proposed models with three conventional models.

1. Introduction

An electromagnetic transducer can act as an actuator by utilizing the Lorentz force generated from the current flowing through the magnetic field [1–3]. It can also act as a sensor by utilizing the motional electromotive force generated from the motion of a coil in the magnetic field [4]. Application examples of the electromagnetic transducer include but are not limited to position control [5,6], sound amplification using loudspeakers [7–11], vibration isolation [12], valve actuation [13], load support magnetic bearings [14], magnetic levitation [15], vehicle suspension [16–18], and energy harvesting [19–21].

Electromagnetic shunt damping is an interesting technique that makes use of actuation and sensing capabilities simultaneously [22–37]. This technique uses a shunted circuit connected across the terminals of an electromagnetic transducer for vibration control and does not use position, velocity, and/or acceleration sensors. In previous studies [22,23], the resonant shunt circuit is designed to be analogous to a dynamic absorber, which is effective in providing nominal performance but is fragile when system parameters such as the natural frequency vary. Hence, precise modeling and accurate parameter estimation are crucial for the design of the shunt circuit.

In previous works, the electrical system in the electromagnetic transducer has been simply modeled by a series connection of the impedance in the coil, the internal resistance, and the motional electromotive force in the coil. The impedance in the coil is typically modeled by the self-inductance [15,16,20–37]. Among the previously published studies, a few consider eddy currents to model the impedance either by adding a shunt resistance in parallel to the self-inductance [8,9] or by the distributed model presented in [10,11]. However, these impedance models do not fully represent the measurement data, as will be shown in this paper, and practical applications continue to require more accurate impedance models, such as that presented here.

This paper presents a method for the sensorless parameter estimation of an electromagnetic transducer; in this method, the parameters of the mechanical, electromechanical coupling, and electrical system models are simultaneously estimated. This framework is consistent with that of electromagnetic shunt damping. The terminal voltage and current of the electromagnetic transducer are measured; specifically, the admittance is measured using an LCR meter or an impedance analyzer, but position, velocity, and/or acceleration sensors are not used. The parameter estimation is formulated by the weighted nonlinear least-squares method; in addition, the selection of the initial estimates for the numerical optimization is discussed in detail. The preliminary idea of this paper has been presented in [38,39], in which the method for the sensorless parameter estimation of an electromagnetic transducer is introduced only for the self-inductance to construct the impedance model. Inspired by the previous works [8–11,40], the present pa-

* Corresponding author.
E-mail addresses: toru.ikegame@nagoya-u.jp (T. Ikegame), kentaro.takagi@nagoya-u.jp (K. Takagi), inoue.tsuyoshi@nagoya-u.jp (T. Inoue), jikuya@se.kanazawa-u.ac.jp (I. Jikuya).

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per introduces novel impedance models that consider eddy currents. The basic physical principles of electromagnetics, such as Ampere's circuital law, Gauss's law for magnetism, Faraday's law of induction, and Ohm's law are applied to model the impedance, and then, the partial differential equation with variable coefficients is obtained. It is difficult to convert this equation to a transfer function, and therefore, two types of physical simplifications are considered. One impedance model is derived by using spatially uniform parameters and spatially distributed eddy currents. The other impedance model is derived by using spatially nonuniform parameters and spatially lumped eddy currents. The effectiveness of the proposed parameter estimation method and the validity of the proposed models are demonstrated by performing experiments related to both parameter estimation and shunted vibration control, comparing the results obtained by the proposed method with those obtained by three conventional models, as described below.

The remainder of this paper is organized as follows. We start by presenting an overview of the conventional modeling techniques of an electromagnetic transducer for shunted vibration control and then propose novel impedance models that consider eddy currents in Section 2. We then proceed to describe the development of the parameter estimation method in Section 3. We report the demonstration of the proposed parameter estimation method through experiments in comparison with those of the conventional models in Section 4. In Section 5, we present the application of the parameter estimation results to shunted vibration control experiments to evaluate the proposed models and the accuracy of parameter estimation. Finally, we make some concluding remarks in Section 6.

2. Modeling

2.1. Conventional modeling technique for a composite electromechanical system

This subsection introduces a conventional modeling technique for the design and analysis of a composite electromechanical system. The composite system consists of three subsystems: a mechanical system, an electromechanical coupling system, and an electrical system.

In many vibration control systems, a mechanical system is modeled by a simple mass-spring-damper system coupled to an electromagnetic transducer [22,31,38,39], as shown in Fig. 1. The equation of motion is given by

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx(t) = f_d(t) + f_l(t), \tag{1}$$

where m [kg] is the mass, c [Ns/m] is the damping coefficient, k [N/m] is the spring constant, $x(t)$ [m] is the displacement of the mass-spring-damper system, $f_l(t)$ [N] is the Lorentz force generated from the electromagnetic transducer, and $f_d(t)$ [N] is the disturbance force.

An electromechanical coupling system is given by the following pair of equations under suitable assumptions [22,23,31,36,38,39]:

$$f_l(t) = \phi\, i_e(t), \tag{2}$$

$$v_{\text{emf}}(t) = \phi\, \dot{x}(t), \tag{3}$$

where ϕ [N/A or Vs/m] is the electromechanical coupling coefficient, $i_e(t)$ [A] is the current flowing through the electromagnetic transducer, and $v_{\text{emf}}(t)$ [V] is the motional electromotive force.

An electrical system is modeled by the series connection of the impedance of the coil, $Z_c(s)$ [Ω], internal resistance in the coil, R_0 [Ω], and motional electromotive force, $v_{\text{emf}}(t)$, as shown in Fig. 2. The circuit equation is given by

$$v_e(t) - v_{\text{emf}}(t) = R_0 i_e(t) + v_c(t), \tag{4}$$

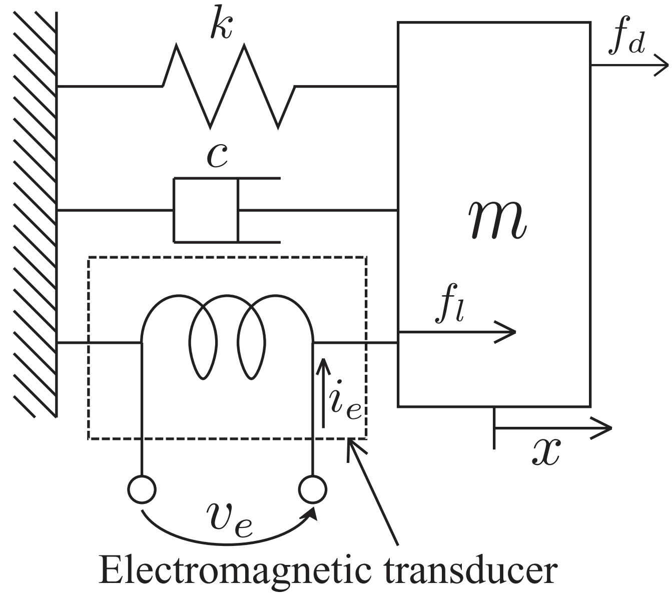

Fig. 1. Simple mass-spring-damper system coupled to an electromagnetic transducer [38].

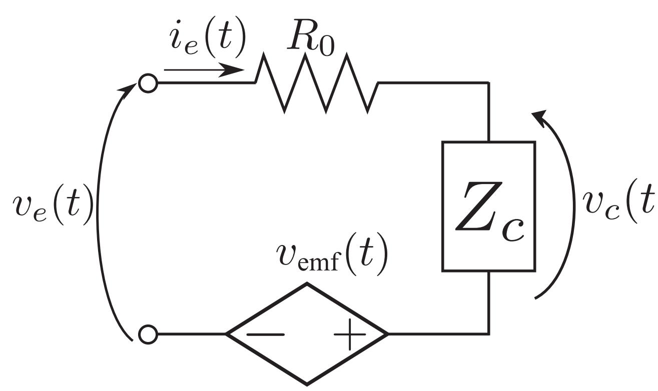

Fig. 2. Electrical system model of the series connection of the impedance of the coil, $Z_c(s)$, the internal resistance in the coil, R_0, and the motional electromotive force, $v_{\text{emf}}(t)$.

where $v_e(t)$ [V] is the voltage across the electromagnetic transducer, and $v_c(t)$ [V] is the voltage across $Z_c(s)$. By taking the Laplace transformation, the impedance of the coil, $Z_c(s)$ [Ω], is defined by

$$Z_c(s) := \frac{\tilde{v}_c(s)}{\tilde{i}_e(s)}, \tag{5}$$

where the tilde represents a signal in the Laplace domain.

The impedance of the coil, $Z_c(s)$ [Ω], has been typically modeled by the self-inductance, L_0 [H], in [15,16,20–37]. In order to distinguish from the other impedance models, the impedance model

$$Z_c^{\text{I}}(s) = L_0\, s \tag{6}$$

is hereafter called the *conventional model I*. The superscript in $Z_c(s)$ indicates the name of the models such as the conventional models or proposed models, as will be shown later.

In addition, the impedance in the coil has also been modeled by adding a shunt resistance, R_μ, in parallel to the self-inductance, L_0, in [8,9]. This shunt resistance was considered to be largely due to eddy current loss [8]. This impedance model, which is hereinafter called the *conventional model II*, is then given by

$$Z_c^{\text{II}}(s) = \frac{R_\mu L_0 s}{L_0 s + R_\mu}. \tag{7}$$