Available online at www.sciencedirect.com
ScienceDirect
IFAC PapersOnline CONFERENCE PAPER ARCHIVE
IFAC-PapersOnLine 49-21 (2016) 074–079

Position Observation for Proportional Solenoid Valves by Signal Injection

Tristan Braun * **Johannes Reuter** * **Joachim Rudolph** **

* *Institute of System Dynamics, Konstanz University of Applied Sciences, 78462 Konstanz, Germany. tbraun/jreuter@htwg-konstanz.de*
** *Chair of Systems Theory and Control Engineering, Saarland University, Campus A5 1, 66123 Saarbrücken, Germany. j.rudolph@lsr.uni-saarland.de*

Abstract: The method of signal injection is investigated for position estimation of proportional solenoid valves. A simple observer is proposed to estimate a position-dependent parameter, i.e. the eddy current resistance, from which the position is calculated analytically. Therefore, the relationship of position and impedance in the case of sinusoidal excitation is accurately described by consideration of classical electrodynamics. The observer approach is compared with a standard identification method, and evaluated by practical experiments on an off-the-shelf proportional solenoid valve.

Keywords: Hydraulic Actuators, Electromagnetic devices, Magnetic Fields, Observers, Parameter Estimation

1. INTRODUCTION

Position estimation in electromagnetic actuators (EMA) is highly desired in industrial applications. On the one hand, this is motivated by omitting costly sensors, and on the other hand to realize on-board diagnostics. A common method is to determine the position-dependent inductance from the current ripple of a pulse-width-modulated (PWM) control voltage, as it is proposed e.g., by Rahman et al. (1996); Glück et al. (2011); Dulk and Kovacshazy (2015). One disadvantage of this method is the high sampling frequency that is needed to record the current-wave form exactly. The method of signal injection is frequently suggested to estimate the position for self-sensing magnetic bearings as well as for synchronous electrical motors, see e.g. Maslen (2009); van Schoor et al. (2013); Jebai et al. (2012). However, this method is rarely proposed in the literature with respect to position estimation for solenoid valves, although the self-sensing approach is in principle transferable. The essential procedure is the following. By the change of position of the rotor or the plunger, a change of inductance as well as eddy current resistance occurs (Pawelczak and Trankler (2004)). Via an analysis of the response of the injected signal, the parameters, and therefore, the actual position can be determined. In Wu and Chen (2009) the position of a linear EMA is determined via phase detection of an underlying resonance circuit that is excited by the injected sinusoidal signal. In Maridor et al. (2009), the position information is extracted from the magnitude of a sinusoidal voltage near the resonance frequency. In both approaches look-up tables are created from experimental data that map the position against the measured quantities. The present paper makes the following contributions. On the one hand, relationships from classical electrodynamics are used to derive a clear and detailed model that describes the influence of sinusoidal currents on the inductance and eddy current resistance, dependent on the position. On the other hand, a control theoretic approach is proposed to determine the position. To this end, a numerically efficient reduced order observer is designed. The position estimate is obtained by an inversion of the model of the estimated parameters, therefore, no look-up tables have to be created. The approach is experimentally evaluated on an off-the-shelf proportional directional solenoid valve. To compensate the influence of temperature variations, a simple updating scheme is proposed to correct the value of the copper resistance that occurs in the model.

The structure of the paper is as follows. In Section 2 a frequency and position-dependent representation of both the ohmic and the inductive portion of the impedance is mathematically derived from the one-dimensional diffusion equation. Section 3 concerns the observer design to estimate the position-dependent parameters. Section 4 demonstrates the observer approach on an off-the-shelf solenoid valve, where observations are validated by the signals of the integrated position transducer. Furthermore, the capability of temperature compensation is shown for a test scenario. Finally, in Section 5 the paper concludes with an outlook for future work.

2. ELECTROMAGNETIC MODEL

The voltage drop V over the coil of an EMA can be described by $V = R_{\mathrm{Cu}}\, i + V_{\mathrm{i}}$, with the current i in the coil, the copper resistance R_{Cu}, and the induced voltage V_{i}, which is the derivative w.r.t. time of the flux linkage $\Psi(i,x)$, i.e. $V_{\mathrm{i}} = \dot{\Psi}(i,x)$. The flux linkage depends on the current and the position x of the iron portion in the magnetic field. Therefore, V can be written as

$$V = R_{\mathrm{Cu}}\, i + \frac{\partial \Psi(i,x)}{\partial i}\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\partial \Psi(i,x)}{\partial x}\frac{\mathrm{d}x}{\mathrm{d}t}, \qquad (1)$$

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.513

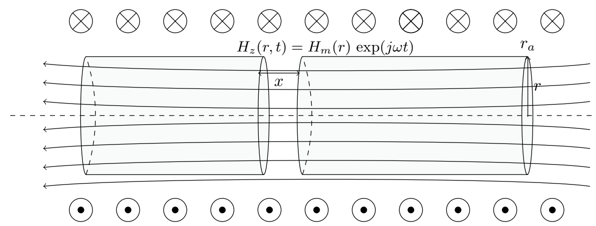

Fig. 1. Approximated solenoid by a cylinder with air gap in the magnetic field.

where the second term accounts for the self-induction due to a change in the current i, and the right term is the back-electromotive force that is proportional to the velocity of the plunger moving in the magnetic field. This term can be neglected if movements are slow. Furthermore, if the currents are small enough that a constant permeability of iron μ can be assumed, (1) simplifies to

$$V = R_{\mathrm{Cu}}\, i + \frac{\partial \Psi(i,x)}{\partial i}\frac{\mathrm{d}i}{\mathrm{d}t} = R_{Cu}\, i + \frac{\partial (L_{\mathrm{s}}(x)\, i)}{\partial i}\frac{\mathrm{d}i}{\mathrm{d}t}$$
$$= R_{\mathrm{Cu}}\, i + L_{\mathrm{s}}(x)\,\frac{\mathrm{d}i}{\mathrm{d}t},$$

with differential or self-inductance $L_{\mathrm{s}}(x)$. However, if $t \mapsto i(t)$ is a periodic function of time, this model must be enhanced in order to include eddy current effects, which is investigated below for sinusoidal excitation.

2.1 Model for Sinusoidal Excitation

To describe the effects of a sinusoidal current on the parameters of an EMA, a model that accounts for eddy current effects is derived (based on Fischer (1976), see also Knoepfel (2000)). Therefore, it is assumed that the solenoid can be represented by an iron cylinder with air gap in the magnetic field, as it is depicted in Fig. 1. For the sake of simplicity, solely the component in axial direction of magnetic field strength $\mathbf{H}$, i.e. $H_z(r,t)$, with radial coordinate r is considered. Then, the diffusion equation (in polar coordinates) reads

$$\frac{\partial^2 H_z(r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial H_z(r,t)}{\partial r} - \mu\sigma\frac{\partial H_z(r,t)}{\partial t} = 0, \qquad (2)$$

with permeability μ, and conductivity σ. Assuming sinusoidal excitation, the magnetic field strength can be written with complex argument as $H_z(r,t) = \underline{H}_{\mathrm{m}}(r)\exp(j\omega t)$, with frequency ω and amplitude $\underline{H}_{\mathrm{m}}(r)$. Inserting this expression in (2), yields the zero-order Bessel differential equation

$$\frac{\partial^2 \underline{H}_{\mathrm{m}}(r)}{\partial r^2} + \frac{1}{r}\frac{\partial \underline{H}_{\mathrm{m}}(r)}{\partial r} + k^2 \underline{H}_{\mathrm{m}}(r) = 0, \qquad (3)$$

with complex number $k^2 = -j\,\omega\mu\sigma$ (Watson (1966)). Let $\underline{H}_{\mathrm{m}}(r)$ be defined on $(0, r_a)$, where r_a is the outer radius, then the boundary conditions are given by $\partial \underline{H}_{\mathrm{m}}/\partial r(0) = 0$, since the eddy current density vanishes at $r = 0$, and $\underline{H}_{\mathrm{m}}(r_a) = \hat{H}$. The solution of (3) with zero-order modified Bessel function of the first kind I_0 is given by

$$\underline{H}_{\mathrm{m}}(r) = \hat{H}\frac{I_0(k\,r)}{I_0(k\,r_a)},$$

where the underline indicates that it is complex. The magnetic flux $\underline{\Phi}$ can be obtained by Gauss' law as $\underline{\Phi} = \mu\int_A \underline{H}_{\mathrm{m}}(r)\, r\,\mathrm{d}r\,\mathrm{d}\varphi$, where $A = \pi\, r_a^2$ is the area perpendicular to the magnetic field lines. This can be solved analytically, and reads

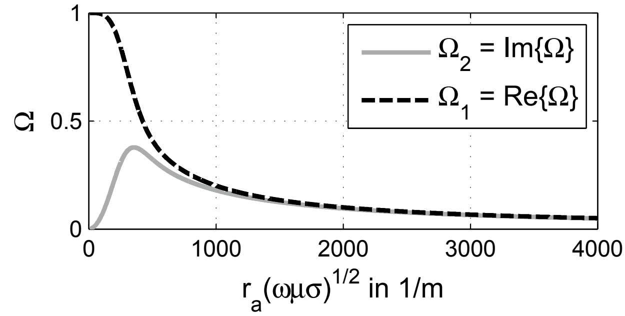

Fig. 2. Frequency-dependent weights of eddy current resistance and inductance in a solenoid.

$$\underline{\Phi} = \pi\, r_a\,\mu\,\hat{H}\,\frac{2}{k}\frac{I_1(k\,r_a)}{I_0(k\,r_a)}, \qquad (4)$$

where I_1 is the first-order mod. Bessel function of the first kind. By considering Ampère's law, the stationary part of magnetic field strength can be obtained as

$$\hat{H} = \frac{N\,i}{l + \mu_r\,x}, \qquad (5)$$

where x denotes the air gap, i is the current circulating through N windings, μ_r is the relative permeability of iron, and l is the effective length of magnetic field lines. Assuming μ_r is constant, the complex inductance reads

$$\underline{L} = N\,\underline{\Phi}/i. \qquad (6)$$

With (4) and (5), the complex inductance (6) can be split in real and imaginary parts as

$$\underline{L} = \Omega_1\frac{N^2\pi\, r_a^2\,\mu_0}{l/\mu_r + x} - j\,\Omega_2\frac{N^2\pi\, r_a^2\,\mu_0}{l/\mu_r + x}, \qquad (7)$$

where Ω_1 and Ω_2 denote the real and imaginary part of the complex function

$$\underline{\Omega}(k\,r_a) = \frac{2}{k}\,\frac{I_1(k\,r_a)}{I_0(k\,r_a)},$$

respectively. Finally, the impedance $\underline{Z} = R_{\mathrm{Cu}} + j\,\omega\,\underline{L}$ is obtained with (7) as

$$\underline{Z} = R_{\mathrm{Cu}} + [\omega\,\Omega_2 + j\,\omega\,\Omega_1]\,L_{\mathrm{s}}(x),$$

where

$$L_{\mathrm{s}}(x) = \frac{N^2\pi\, r_a^2\,\mu_0}{l/\mu_r + x}$$

is the self-inductance in the case of stationary currents. In Fig. 2.1 the graphs of Ω_1 and Ω_2 are plotted. It is obvious that for $\omega \neq 0$ the ohmic resistance is raised by the amount

$$R_{\mathrm{ed}}(x;\omega) = \omega\,\Omega_2 L_{\mathrm{s}}(x), \qquad (8)$$

which is called the eddy current resistance, and increases first proportional to ω, where the inductance

$$L(x;\omega) = \Omega_1 L_{\mathrm{s}}(x)$$

decreases for increasing ω. The corresponding equivalent circuit is shown in Fig. 3. The qualitative behavior of this model is consistent with the rate-dependent permeability model for a magnetic bearing model used in Ranft et al. (2011). Here, moreover, the model is verified by experimental results in Section 4.