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A Computationally Efficient Commutation Algorithm for Parasitic Forces and Torques Compensation in Ironless Linear Motors

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Abstract: Ideally, ironless linear motors can reach very high precision with simple classical commutation using three-phase sinusoidal currents. However, in reality, due to deviations from the design parameters, there are various parasitic forces and torques for which the classical commutation cannot compensate. An alternative solution is to formulate the commutation as an optimization problem and solve it numerically. This paper proposes a new optimization algorithm which is computationally efficient and well-suited to the commutation problem in the sense that it is capable of compensating for parasitic forces and torques while minimizing the dissipated power in the motors. Simulation results with a finite element method model are presented to demonstrate the effectiveness of the proposed commutation algorithm.

1. INTRODUCTION

Ironless linear motors (ILMs), also known as coreless linear motors, are widely used in precision positioning systems due to their extremely high precision. An ideal ILM produces only propulsion force. There is no parasitic force and torque in non-driving directions due to symmetrical stator design. The desired propulsion force can be obtained accurately with low ripple just by using simple three-phase sinusoidal currents, since there is no cogging force.

Due to this designed high precision, there are very few research works on compensation for parasitic effects in ILMs in the literature. Most of the research focuses on optimizing the topology design (Ferkova et al., 2008; Tavana et al., 2012; Li et al., 2012, 2013; Zhang et al., 2014). However, in reality, there will always be deviations from the design parameters due to manufacturing tolerances. These deviations result in various parasitic forces and torques which need to be compensated by control. Some control techniques to compensate for the parasitic propulsion force in ILMs can be found in (Röhrig, 2005, 2006; Li et al., 2009; Bascetta et al., 2010). Recently, a method to compensate for both parasitic propulsion force and parasitic normal force was proposed in (Nguyen et al., 2015). However, in all of the above-mentioned methods, the parasitic torque is neglected. The aim of this paper is to develop a feedback linearization algorithm, which is known as commutation in linear motors literature, to compensate for parasitic forces and torques in ILMs simultaneously.

Commutation, or feedback linearization, in linear motors is a mechanism that calculates the required currents in the coils to achieve the desired forces and torques. The classical commutation makes use of three-phase sinusoidal current waveforms, which results in propulsion force ripples, even in the ideal case. There are more advanced commutation methods which can completely eliminate the ripples in the propulsion force. In general, commutation can be formulated as an optimization problem which minimizes the dissipated power in the coils, subject to the constraints that the desired forces and torques are obtained, and the sum of the currents is zero if the coils are connected in star configuration. This optimization problem can be solved using numerical optimization (Meeker, 1996; Lovatt and Stephenson, 1997; Röhrig, 2003; Ahmed and Taylor, 2006; Shinnaka and Sagawa, 2007; Ruben and Tsao, 2012; Ahmed and Taylor, 2015; Moehle and Boyd, 2015), which is in general computationally expensive. In the case when the relation between the force vector and the current vector is linear, this optimization problem can be solved analytically by eliminating equality constraints (Rehman and Taylor, 1995; Röhrig, 2005, 2006; Dwari and Parsa, 2008; Ridge et al., 2011), by using Lagrange multipliers (Wu and Chapman, 2005; Baudart et al., 2010, 2013), or by using the minimum 2-norm generalized inverse (van Lierop et al., 2009; Ruben and Tsao, 2012). These analytical commutation methods can be applied to ideal ILMs, since the propulsion force is linear with the currents in the coils.

However, in nonideal ILMs where the coils are not exactly in the center of the air gap, the parasitic forces and torques are quadratic functions of the current vector due to the presence of reluctance forces (Nguyen et al., 2015). The commutation problem therefore becomes a quadratic optimization problem with quadratic equality constraints. In general, it is difficult to find an analytical solution and hence numerical methods are necessary for solving the commutation problem.

A common way to solve a quadratic optimization problem with quadratic equality constraints is to formulate the set of optimality conditions, which are known as the Karush-Kuhn-Tucker (KKT) conditions (Kuhn and Tucker, 1951), and solve these equations numerically using Newton's method. This optimization approach was used to solve the commutation problems that involved quadratic equality constraints in (Meeker, 1996; Overboom et al., 2015). The disadvantage of this approach is that it introduces additional optimization variables, i.e. Lagrange multipliers, which increases the complexity of the problem. In addition, this approach requires evaluation and storing of the Hessian matrix. This increases the computation time per iteration and the amount of memory required, especially for large-scale problems.

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To reduce the computational load, this paper proposes an optimization algorithm which bypasses the optimality conditions and implements a direct iterative search for the optimum. The idea is inspired by the fact that the commutation optimization problem is actually a special type of optimization problems which searches for the minimum 2-norm solution of an underdetermined system of equations. A well-known method to find a solution of an underdetermined system of equations is the generalized Newton's method (Levin and Ben-Israel, 2001). However, this method only searches for a feasible solution of the system of equations.

This paper proposes a new algorithm which searches for the minimum 2-norm solution of the system of equations. The algorithm is the interpolation between the generalized Newton's iteration and a proposed minimum 2-norm iteration. It can be proved that the proposed algorithm converges locally to the minimum 2-norm solution of the underdetermined system of equations. Additionally, the computational cost is low since the algorithm does not introduce additional optimization variables and does not require evaluation of the Hessian matrix. The algorithm is then applied to solve the commutation problem in nonideal ILMs. Simulation results with a finite element method (FEM) model are presented to verify the performance of the proposed algorithm.

The remainder of this paper is organized as follows. Section 2 describes the topology and the analytical model of an ILM. The commutation problem in ILMs is formulated as an optimization problem in Section 3. Section 4 presents the proposed numerical optimization algorithm that can be applied to solve the commutation problem. The simulation results using the proposed algorithm are shown in Section 5. Section 6 summarizes the conclusions.

1.1 Notation

Let $\mathbb{N}$ denote the set of natural numbers and $\mathbb{R}$ denote the set of real numbers. Let $\mathbb{R}^n$ denote the set of real column vectors of dimension n, and $\mathbb{R}^{n\times m}$ denote the set of real $n\times m$ matrices. For a vector $x\in\mathbb{R}^n$, $x_{[i]}$ denotes the ith element of x. The Nabla symbol ∇ denotes the gradient operator. For a vector $x\in\mathbb{R}^n$ and a mapping $\Psi:\mathbb{R}^n\to\mathbb{R}$

$$\nabla_x\Psi(x)=\left[\frac{\partial\Psi(x)}{\partial x_{[1]}}\ \frac{\partial\Psi(x)}{\partial x_{[2]}}\ \cdots\ \frac{\partial\Psi(x)}{\partial x_{[n]}}\right]. \quad (1)$$

The notation $0_{n\times m}$ denotes the $n\times m$ zero matrix and I_n denotes the $n\times n$ identity matrix. Let $\|\cdot\|_2$ denote the 2-norm.

2. IRONLESS LINEAR MOTOR

This section describes the topology and the analytical model of an ILM.

2.1 Topology

A cross-sectional view of an ILM is shown in Fig. 1. An ILM contains a stationary part called the stator and a moving part called the translator. The stator consists of two permanent magnet arrays mounted on two iron plates. The translator contains one or multiple sets of three-phase coils placed in the center of the air gap between the two magnet arrays. The motor is actuated in the x-direction and produces no force in other directions in the ideal case.

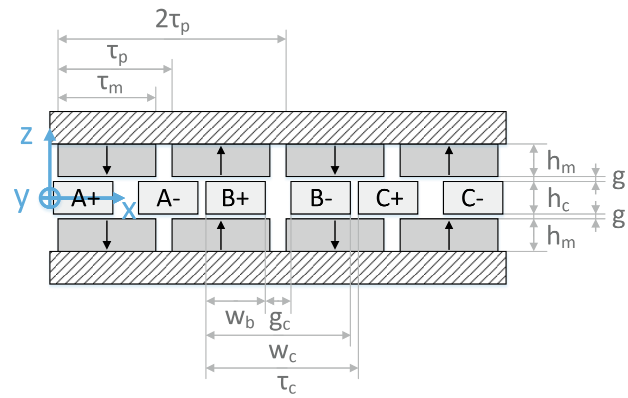

Fig. 1. Cross-sectional view of an ironless linear motor.

2.2 Modeling

The main force components in a nonideal ILM are Lorentz force and reluctance force. The propulsion force F_x, the normal force F_z and the torque T_y can be modeled as (Nguyen et al., 2016)

$$F_x=K_x(q)i, \quad (2)$$

$$F_z=K_z(q)i+i^TG_z(q)i, \quad (3)$$

$$T_y=K_t(q)i+i^TG_t(q)i, \quad (4)$$

where q is the position vector of the translator:

$$q=[x\ z]^T, \quad (5)$$

i is the vector of the currents through the coils:

$$i=\left[i_{A_1}\ i_{B_1}\ i_{C_1}\ \ldots\ i_{A_{N_c}}\ i_{B_{N_c}}\ i_{C_{N_c}}\right]^T, \quad (6)$$

N_c is the number of sets of three-phase coils. Here, i is a vector of dimension $n=3N_c$; $K_x(q)$, $K_z(q)$, $K_t(q)$ are $[1\times 3N_c]$ matrices; $G_z(q)$, $G_t(q)$ are $[3N_c\times 3N_c]$ matrices which are dependent on the position q of the translator. In equations (2)-(4), the terms which are linear in i model the Lorentz forces and torque. The terms which are quadratic in i model the reluctance forces and torque.

The matrices $K_x(q)$, $K_z(q)$, $K_t(q)$, $G_z(q)$ and $G_t(q)$ represent the relation between the currents in the coils and the resulting forces and torques. They can be determined from the geometry of the motor using first principle modeling methods. In this paper, Fourier modeling method is employed since it provides an analytical model of the motor. The main idea of this modeling method is to approximate the magnetic source term distribution by Fourier series. The magnetic field solution is then obtained by solving Laplace and Poisson equations (Zhu et al., 1993; Gysen et al., 2010). In order to model the parasitic effects such as the end effect or the variation in remanent magnetization of individual magnets, the whole motor length is modeled as one Fourier period in this paper. Details on Fourier modeling of ILMs can be found in (Nguyen et al., 2015) and the references therein.

For brevity, the index (q) will be omitted in the remainder of the paper.

2.3 Model validation

For validation, the derived Fourier model is compared with the FEM model. An example motor with the design parameters