Sensors and Actuators A 234 (2015) 375–383

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Analytical modeling of linear oscillating motor with a mixed method considering saturation effect

Tianyi Wang [a], Liang Yan [a,b,*], Zongxia Jiao [a,**], Ping He [a]

[a] Department of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[b] Research Institute of Beihang University in Shenzhen, Shenzhen 518000, China

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 26 August 2015
Accepted 7 September 2015
Available online 15 September 2015

Keywords:
Linear oscillating motor
Analytical model
Magnetic potential vector
3D equivalent magnetic circuit
Finite-element method

ABSTRACT

Linear oscillating motor receives much attention recently due to direct and efficient linear motion output. In order to achieve high thrust and eliminate eddy current effect, circumferential silicon steel stack is usually utilized in stator as a universal topology design. However, circumferential arrangement of silicon steel introduces 3D magnetic circuit, which complicates the design process and cannot be solved using conventional modeling method. In addition, it leads to severe magnetic saturation effect and must be taken into accounts in the analytical model for accurate results. In this paper, a novel mixed analytical modeling method for linear oscillating motor with silicon steel stator is proposed. Magnetic potential vector (MPV) and 3D equivalent magnetic circuit (3D-EMC) methods are combined together in this mixed model. Magnetic potential vector method sets up the coarse flux density distribution, while 3D equivalent magnetic circuit method is used for refinement considering saturation. Moreover, the performance between radial and parallel magnetized structure is compared based on this model. For validation, FEM and experimental results are compared with the proposed model and proves its effectiveness and accuracy, which can be used in further motor structure optimization. It may also act as a universal guidance to other PM motor design.

1. Introduction

Linear oscillating motor provides reciprocate linear movement directly without motion conversion mechanisms, which can be used in linear pumps, compressors, LEHA applications and so on [1–3]. Due to high force density, moving-magnet type linear oscillating motor is the research trend compared to moving-coil and moving-iron types [4]. For the mover of moving-magnet motor, the magnets are mounted on the mover tube and guided by linear bearings on both ends. While for the stator, it supplies magnetic field conducting paths for the whole magnetic circuit generating by magnets and coils. Thus, the stator matters a lot for electromagnetic performance of motor. On one hand, high permeability is preferred for output performance, because it contributes to low magnetic resistance and high flux density. On the other hand, high frequency reciprocate movement of mover excites severe eddy current effect, which causes undesirable heat losses and thrust decline and should be avoided. Therefore, the selection of stator material should account for these two aspects.

There are mainly three types of stator materials in existing motor designs. Some researches utilize electrical iron as the stator material [5]. It is convenient for machining in different shapes because of the features of metal. Moreover, it has relatively high permeability and saturation flux density, which contributes to high static thrust and low saturation. But the eddy current effect is obvious, causing severe heat loss and decline of dynamic output force, especially for high speed applications. In order to eliminate eddy current, soft magnetic composite such as Somaloy series in *Höganäs* is introduced in stator design [6–8]. It is made up of micro iron powder with continuous insulation layer compacting at high pressure. Due to the existence of nonconductive insulation layer, the eddy current is decreased considerably. But the magnetic permeability is weakened at the same time, which leads to electromagnetic performance decline.

Silicon steel has been used in transformers and rotary motors since it has high permeability and low eddy current simultaneously [9–11]. Thus, it is the optimal option for stator design currently for both output and efficiency. While for linear motor, the arrangement of silicon steel needs to be circumferentially stacked for easy fabrication and assembly. Thus, it is inevitable to introduce 3D magnetic circuit into silicon steel stator of linear

* Corresponding author at: Department of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China.
** Corresponding author.
E-mail addresses: wangtianyi@buaa.edu.cn (T. Wang), lyan1991@gmail.com (L. Yan), zxjiao@buaa.edu.cn (Z. Jiao), helping@buaa.edu.cn (P. He).

http://dx.doi.org/10.1016/j.sna.2015.09.014
0924-4247/

motor, in which the flux density is no longer symmetrical about z axis, making it complicated for the modeling and design process. Chai [12] conducted 3D FEM analysis on PM linear motor with laminated modules. Though FEM analysis has accurate results, it is time and memory consuming, not suitable for parameter design and optimization. Equivalent surface current and EMC methods are also used to derive flux density of single magnet and in the air gap [13–15]. It makes simplifications by assuming the magnetic circuit has symmetrical structure, ignorant of the silicon steel laminations effects. Thus, the magnetic field model accuracy suffers a lot. Furthermore, EMC method has only lumped parameters and cannot reflect precise flux density and thrust changes. Thus, EMC method alone cannot deal with this modeling problems effectively. Wang researches into linear motor magnetic field modeling based on MPV method [16–18]. It is a distributed parameter method with exact flux density distribution. However, in this method, the stator permeability is assumed to be infinite for simplification and has symmetric structure along z axis. Thus, the saturation and 3D magnetic circuit phenomenon cannot be modeled exactly. Zhu proposes a compensation method for saturation based on EMC [19]. Similarly, Hemeida puts forward a mixed modeling method for fast and accurate calculations [20]. However, all these researches are dealing with 2D symmetrical structure. While for 3D magnetic field modeling with saturation accounted, there is no suitable method for convenient and accurate modeling analytically.

To deal with the problems in modeling of linear motor with silicon steel stator, this paper proposes a novel modeling method with MPV and 3D-EMC combined together. The MPV method calculates the magnetic field results coarsely, providing the basic information of flux density distribution. Based on this knowledge, 3D-EMC model is set up in details, taking saturation into consideration. Then, the EMC results are used for compensation of MPV results. Accordingly, the accurate flux density and thrust can be derived. FEM analysis and experimental verification are conducted for effectiveness proof of this proposed model. This method can also be applied in other PM motor modeling process with severe saturation or 3D magnetic circuit circumstances.

For clarification, the remaining contents of this paper are organized as follows. Section 2 gives the explanation of mechanical and magnetic circuit structure of motor with leading parameters denoted. Then, the flux density including open-circuit and armature reaction field is resolved in details in Section 3. Based on the flux density results, Section 4 gives the derivation of EMF, thrust and inductance. For saturation compensation, 3D-EMC method is proposed in Section 5 with corrected factor calculated. FEM validation and analysis are conducted in Section 6. Section 7 provides the experimental results and performance of motor for verification. Finally, conclusion is made in Section 8.

2. Motor structure and magnetic topology

The structure of tubular linear oscillating motor under research is shown in Fig. 1. Fig. 1a shows the main components of linear motor including mover and stator parts. For mover, Halbach array are mounted on back-iron with self-shielding effects [21]. Integrated position sensor based on hall effect is used for stroke measurement and position feedback [22]. In order to enhance system efficiency, high stiffness disk spring stacks are introduced to create mechanical resonance. While for stator, silicon steel laminations with slots are utilized for conducting flux. The silicon steel laminations are arranged circumferentially as shown in Fig. 1b to eliminate eddy current efficiently and facilitate fabrication simultaneously. Six lamination stack segments form a whole ring. Inevitably, it leaves considerable air region between each lamination stack and causes saturation in stator. For further magnetic

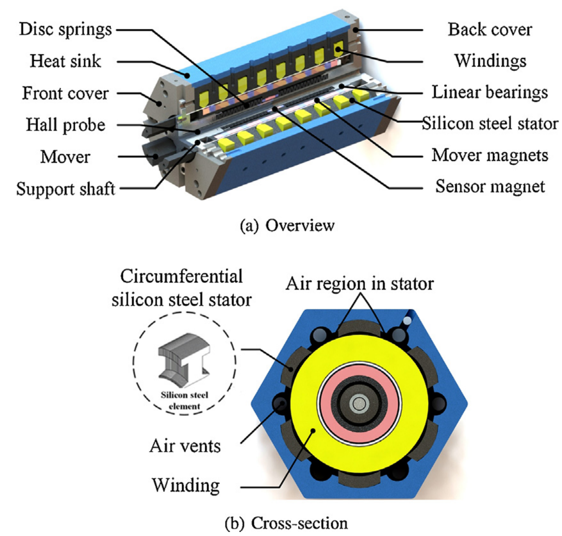

Fig. 1. Structure of linear oscillating motor.

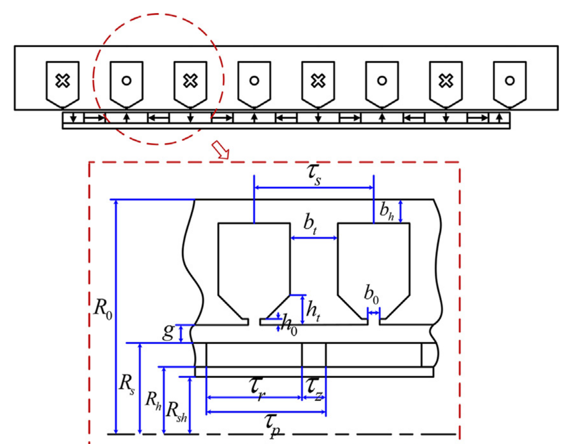

Fig. 2. Magnetic topology and leading parameters.

modeling, the magnetic topology of this motor is shown in Fig. 2 with leading parameters denoted.

3. Modeling of magnetic field distribution

In this section, MPV method is used for both open-circuit and armature reaction field modeling. Open-circuit model refers to the magnetic field generated by PMs and is the basis of calculating thrust. While armature reaction field is created by windings, which is closely related to flux linkages, inductance and EMF of motor.

3.1. Open-circuit magnetic field distribution

The following assumptions are made in advance for simplification.

i The magnetic materials have constant and uniform relative permeability μ_r.
ii The saturation effect in mover tube and stator silicon steel is ignored.
iii The slot effects of stator is compensated by Carter coefficients.
iv The whole model is made infinitely long and symmetrical along z axis with series of actual motor units separated by long enough air region, as shown in Fig. 3.