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FULL LENGTH ARTICLE

Modeling and analysis of mover gaps in tubular moving-magnet linear oscillating motors

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Abstract A tubular moving-magnet linear oscillating motor (TMMLOM) has merits of high efficiency and excellent dynamic capability. To enhance the thrust performance, quasi-Halbach permanent magnet (PM) arrays are arranged on its mover in the application of a linear electro-hydrostatic actuator in more electric aircraft. The arrays are assembled by several individual segments, which lead to gaps between them inevitably. To investigate the effects of the gaps on the radial magnetic flux density and the machine thrust in this paper, an analytical model is built considering both axial and radial gaps. The model is validated by finite element simulations and experimental results. Distributions of the magnetic flux are described in condition of different sizes of radial and axial gaps. Besides, the output force is also discussed in normal and end windings. Finally, the model has demonstrated that both kinds of gaps have a negative effect on the thrust, and the linear motor is more sensitive to radial ones.

1. Introduction

Tubular moving-magnet linear oscillating motors (TMMLOMs) are specific linear actuators that produce a high-frequency reciprocating motion. Their outstanding characteristics, such as efficiency, dynamic performance, and simple structure, give their broad application prospect, but their model has not been clearly described and their structure has not been optimized adequately. TMMLOMs work at a designed frequency with the stroke of mover oscillating no more than one pole pitch, which are widely applied in many equipment, such as artificial hearts, compressors, refrigerators, etc.[1–5] As short-travel actuations are propelled directly without conventional cranks, TMMLOMs enjoy a 20%-30% better efficiency compared with rotary motors in the application of household refrigerator compressors.[5] By enlarging the power whilst reducing acoustic noise and vibrations accordingly, TMMLOMs are tested for air-conditioner compressors with an efficiency of over 92% at a rated condition.[6] Due to a relatively higher frequency response benefited from the absence

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of rotor inertia in the rotary mechanism, TMMLOMs are developed to drive the servo pump in a hydraulic system.[7] Meanwhile, TMMLOMs are utilized in linear electro-hydrostatic actuators in more-electric aircraft systems with a high power density.[8] In addition, a cooperative configuration is introduced where two movers of dual TMMLOMs work with a phase angle of $\pi/2$.[9] A reliable coordinated control of two TMMLOMs requires a regulation based on an accurate model. Furthermore, a powerful output with limited space and restricted mass in aircraft also needs more optimized analysis of the motor structure and principle based on a precise calculation of the air-gap magnetic field. A comprehensive model, therefore, is indispensable for TMMLOMs.

Some well-known modeling optimization approaches, such as changing the direction of magnetization on a mover, configuring the groups of PM arrays on movers, decreasing the slots of the stator, and regulating the split ratio of E-Core PMs, have been confirmed to improve the characteristics of TMMLOMs. However, current research pays little attention to the effects of mover gaps (air gaps among PMs or between PMs and materials) which exist inherently in the segments of PMs. Despite the fact that the effects of discontinuity on PMs has not been proven to be very prominent, an introduction of their effects on the distribution of a magnetic field through an analytical mathematics and simulation model is also a necessity when aiming to optimize a TMMLOM for a high-performance aeronautical facility and create a dual-motor collaborative control strategy on this basis.

Many studies about the TMMLOMs have been published over the last three decades, focusing on improving the output performance analytically and experimentally through reducing the mover weight and increase the frequency.[3,4]

The topology of PMs is an important factor that influences the output performance. Kim et al. proposed a linear oscillatory actuator whose magnetization direction of PMs was parallel to the stroke axis,[10] and the machine shared a high-power density and a low-cogging force. A transient model of this motor was validated experimentally.[11] In the contrary, Kim et al. discussed a TMMLOM with its magnetization direction perpendicular to the motion direction.[12,13] The magnetic field was analyzed by an analytical model, and the prototype gave capabilities of high force density and low detent force. By the ways of magnetic vector potential and cylindrical coordinate formulation, Wang et al. presented a general framework for TMMLOMs. His solutions presented the analytical field distribution for both axial polarized and radial polarized tubular linear PM motors.[14] The air-gap flux densities of both topologies were compared,[15] and a finite element model showed that the radial attractive force was higher in the axial polarized structures when considering the eccentricity effect.

In a publication series presented by Wang et al., a quasi-Halbach structure of TMMLOMs which was a combination of radial polarized and axial polarized PMs arrays was deeply analyzed,[14,16–19] including an analytical flux expression of the quasi-Halbach topology,[14,16,18] comparative analysis to conventional magnetization methods,[17] and parameters optimizations on the size of the structure.[19] Because of some self-shielding property, the quasi-Halbach PM arrays would reduce the moving mass to improve the dynamic capability and result in a higher flux density.

The coupling between windings and PMs is another area that researchers have focused on. Considering the configuration of stator windings in TMMLOMs, Wang et al. deduced a set of formulations to describe the distribution of magnetic flux theoretically based on Maxwell's equations.[16] Zhu et al. studied a variety of winding arrangements with a PMs assembly.[20–24] A rule was outlined that the stator tooth number was supposed to differ the mover pole number by 1 in TMMLOMs.[20] Subsequently, simulation calculations and experiment validations were finished by Zhu et al., which demonstrated that the E-core wind configuration yielded less flux leakage and performed conducive to the oscillation.[20,22] Eventually, design optimization and prototype validation was implemented for the topology of a TMMLOM with E-type windings and quasi-Halbach PMs.[23,24] This type of motor was further extended into E-type series TMMLOMs,[25] which consisted of multi-pair E-cores with a quasi-Halbach topology to enhance the thrust. Furthermore, Jiao et al. presented compound Halbach PMs in a TMMLOM, whose topology was a dual-layer integration of quasi-Halbach PMs and axial polarized PMs.[26] In Jiao's structure, the conventional back-iron was not needed any more, hence the mover mass could be decreased further with a better dynamic performance.

To improve the properties of a TMMLOM, a stator slot was taken into account by researchers. Bianchi et al. analyzed the factor of a stator slot that affected the force.[15] His research showed that slotless motors shared a higher mean force than slotted ones. Kim et al. designed a slotted TMMLOM[13] and a slotless TMMLOM[12] for an eco-pedal system, and the later presented a smaller force ripple experimentally. An analytical model with a quasi-Halbach magnetized armature and a semi-closed slot stator was given by Chen et al.,[23] and a closed slot structure was employed into a TMMLOM to reduce the cogging force in Liang's paper,[7] of which the leakage permeability was much larger than that of the former. Besides, Kim et al. proposed a novel method for stator lamination to laminate the teeth and yoke of a stator respectively, which decreases the gaps in the stator and multiplies the flux density.

By introducing a Carter coefficient, Wang et al. modified the analytical model of tubular linear PM motors with a slotted stator[14] and a semi-closed slotted stator.[27] They also applied this correction to calculate the distribution of flux density of a TMMLOM with quasi-Halbach PMs. This method was also followed by Wang et al. to model the E-type series TMMLOMs.[28]

Experimental, numerical, and analytical methods are the three normal research approaches on LMMLOM research. Some studies have been implemented entirely experimentally,[6,10,29,30] whose results could exhibit the performance of a motor directly. However, they didn't reveal the principle of LMMLOMs. Numerical approaches have been widely applied in LMMLOM designs,[7,17,31–35] which allow to solve a complex design without much approximation. However, it didn't reflect the relation between topological parameters and the motor performance, which results in a difficulty in optimization.

The key step to model a TMMLOM is to describe the distribution of magnetic flux, resulting from which that analytical methods can be grouped into three categories. One is lumped magnetic circuit models,[7,24,36–38] which consider a motor made of several parts with individual magnetic parameters, and they can only model the motor roughly due to the lumped approximation method. Another choice is the equivalent surface current method, which introduces several layers of surface current to take the place of PMs.[37] Its approximate structure can only