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A Magnetically Levitated Linear-Rotary Guide for Linear-Rotary Motors

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Abstract

This project aims to investigate, develop and fabricate a new type of magnetic levitated rotary linear guide system based on switched reluctance (SR) principle. Its objective is to eliminate the mechanical components (e.g. gears, guide, ball bearings), reduce the mechanical alignment and maintenance cost, and enable the rotary-linear to travel at high speed with high precision and acceleration. The proposed system has the advantages of being contact-free, thus resolving the problems of mechanical wear, friction, noise, heat generation, and "metal dust" contamination. The proposed bearingless switched reluctance motor (BSRM) is very suitable for use in high-precision manufacturing machines, clean-room wafer carrier systems, and high-speed material transport in assembly lines. In this paper, the mechanical structure is introduced. Finite element simulation is performed to validate the design concept and verify the effectiveness of the motor structure.

Keywords: direct-drive, switched reluctance, planar machine, BSRM, linear-rotary guide

1 INTRODUCTION

In industry, high-precision position rotary and propulsion movement is in high demand such as PCB drilling, carving machine, etc. Traditionally, the 2D motion is fulfilled with a rotary motor installed on a linear moving platform. Though this is the commonly used method, it has the disadvantages of reduced accuracy, complex mechanical structure, frequent adjustment and alignment, etc [1].

The purpose of this project is to develop a high performance, direct-drive 2D motion system and it is targeted for industrial automation machines that require both rotation and propulsion movement. By using SR technology, the motor has a simple and robust structure with direct-drive capability [2]. Unlike other types of 2D motion systems, there are no expensive materials or complicated winding structures. The proposed system can be operated under hostile environment with large temperature variations.

2 THE 2D SR MOTOR

Figure.1 shows the layout of the 2D SR motor. The motor has a doubly-salient structure as a common 8/6 rotary SR machine. For rotation, the motor structure ensures a continuous reluctance variation between the rotor and rotary stator at different positions. For propulsion, the rotor is driven by three propulsion coils mounted on the propulsion stator.

3 SYSTEM FORMULATION

The equations that govern the propulsion movement (z-direction) can be described in state-space as the following [3],

$$\dot{I}_k = \frac{1}{L_k}\left(U_k - (R_k + \frac{\partial L_k}{\partial s_x} \cdot v_z)\right) I_k \tag{1}$$

$$\dot{v}_z = (F_z - B_z v_z - F_{Lz}) / M \tag{2}$$

$$\dot{s}_z = v_z \tag{3}$$

where U_k and I_k are the input voltage and current vectors for the *k-th* coil ($k = 1-3$). M, F_z, B_z, v_z, s_z and F_{Lz} are rotor mass, electromagnetic force, friction coefficient, velocity, displacement and load vector along z-direction. R_k and L_k are 3×3 diagonal matrix for resistance and inductance of the propulsion coils.Self-inductance for the 3 coils can be expressed in Fourier series by taking the first order approximation [4].

$$L_a = L_{ls} + L_o + L_\Delta \cos(\frac{2\pi s_z}{p}) \tag{4}$$

$$L_b = L_{ls} + L_o + L_\Delta \cos(\frac{2\pi s_z - \frac{2}{3}\pi p)}{p}) \tag{5}$$

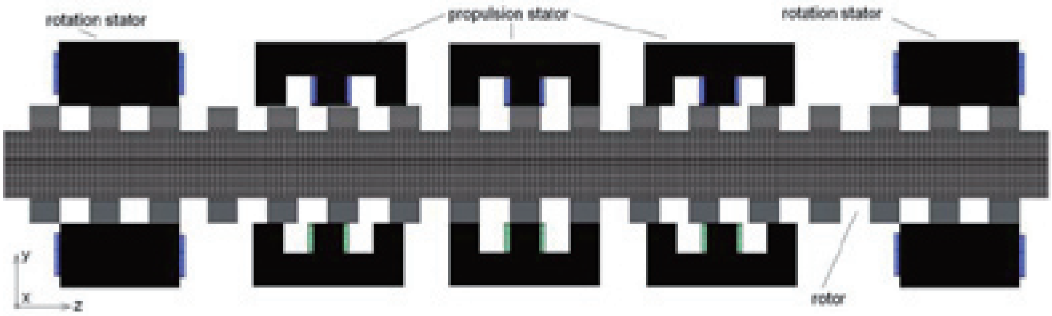


Fig.1 Layout of the 2D motor

$$L_c = L_{ls} + L_o + L_\Delta \cos\left(\frac{2\pi s_z - \frac{4}{3}\pi p}{p}\right) \tag{6}$$

where,

$$L_o = \frac{\mu_0 d^2 N^2}{z} \cdot \frac{p-q}{p} \tag{7}$$

$$L_\Delta \approx \frac{\mu_0 d^2 N^2}{z} \cdot \frac{q}{p} \tag{8}$$

and L_{ls} is the leakage inductance.

Force is calculated as the change of co-energy W_{co} according to displacement as follows,

$$F_z = \frac{\partial W_{co}}{\partial s_z} \tag{9}$$

If the motor is operated under unsaturated region,

$$F_z = \frac{1}{2}\frac{\partial L_k}{\partial s_z} I_k^{\,2} \tag{10}$$

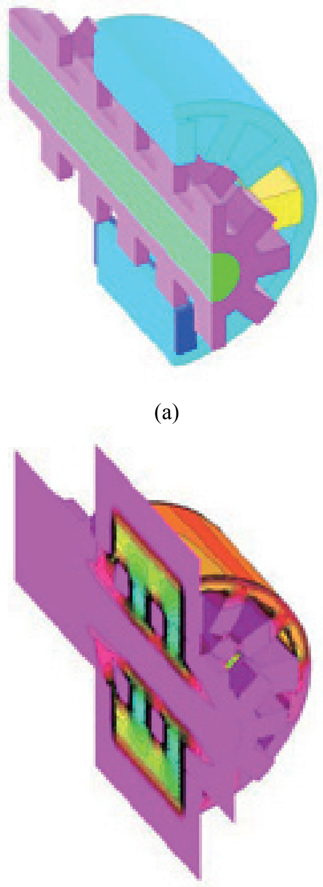
The mathematical model of the rotary movement is similar with a common 8/4 switched reluctance machine and multi-excitation scheme is often applied for better motor performance [5].

4 FINITE ELEMENT SIMULATION

To further verify the electromagnetic characteristics of the motor, a series of finite element analysis (FEA) has been conducted for both the rotation and propulsion movement. The purpose of FEA is to verify that movement from rotation and propulsion is fully decoupled and the whole motor structure is properly designed.

4.1 Rotation performance

Unlike traditional rotary SR motors, the salient rotor teeth are distributed along the circumference and axial direction of the rotor shaft, separated by slots. The rotation stator has a multiple length of rotor pole-pitch along the axial direction as shown in Fig.2 (a). This arrangement not only ensures a smooth rotation but also provides a balanced axial force for any axial positions of the shaft [6]. The motor behaves as a common rotary SR motor for rotation. Therefore, the flux only distributes along the rotor, air gap, and rotation stator along the radial direction only when excited, as shown in Fig.2 (b).



(a)

(b)

Fig.2 Structure (a) and flux distribution (b) of the rotation motor

The axial force under different positions when the rotation stator is excited with different current from 2—5 A is shown in Fig.3. The maximum force at 5A is about 0.14A, which can be neglected from the propulsion movement. Therefore, no decoupling scheme shall be involved.

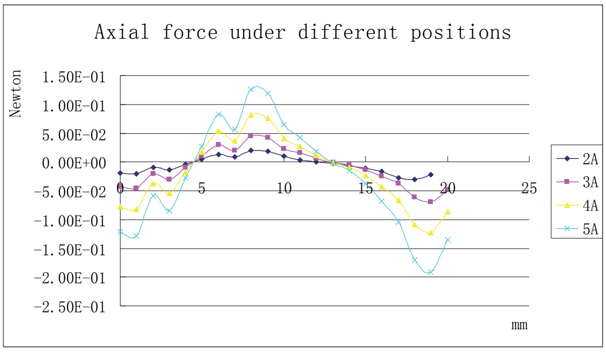
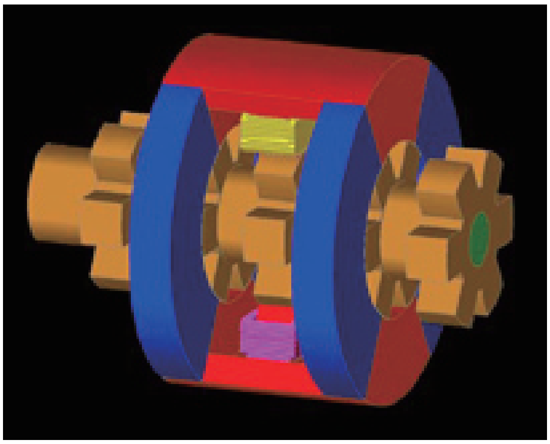


Fig.3 Axial force calculation of the rotation part of motor

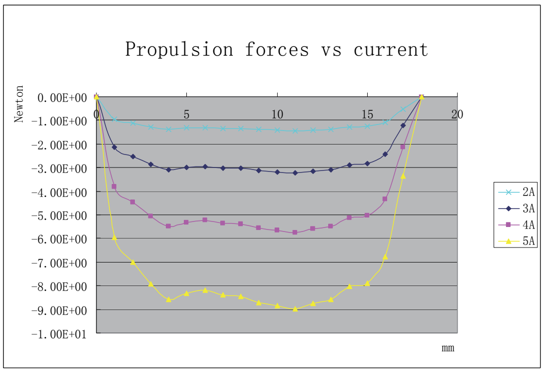
4.2 Propulsion performance

The propulsion ring for one phase is composed of three pairs of stator teeth for better performance and propulsion coils are mounted in the middle stator teeth in series, as shown in Fig.6. The three phases are arranged in such a manner so that when the rotor and stator are fully aligned from one phase, for the other two phases, when excited, the rotor can move in two opposite directions. This configuration conforms to a three-phase linear SR motor to active-stator-passive-mover structure [7].

The propulsion force under different current and positions in half-pole pitch (9 mm) are calculated from FEA as shown in Fig.4. It can be seen from the results that the three-pair stator teeth arrangement provides a smooth force output.



(a)



(b)

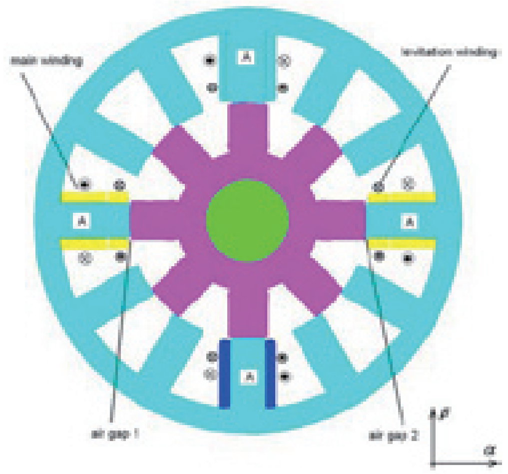
Fig.4 Propulsion forces under different current excitations

4.3 Levitation Scheme

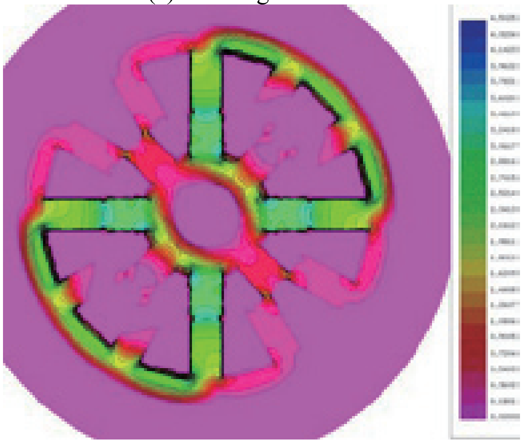
The motor design procedure described above provides a basis for the magnetic levitation of the rotor shaft. The integration of electrical motors and magnetic bearings is applied by using the same stator and rotor structure. To simplify the overall mechanical structure and facilitate magnetic path for levitation, the unbalanced stator winding scheme [9] is used by full utilization of the inherent large magnetic attraction force from the short air gap length. The two rotary motors each have two kinds of stator windings composed of main windings and radial force windings to produce rotation and rotor shaft suspension without mechanical contacts or lubrication.

The rotary and levitation mechanism has a typical 12/8 SR motor structure. Fig.5 shows the stator winding configuration for both rotation and levitation for A-phase. The B-phase and C-phase have the same winding structure and are arranged at one-third and two-thirds rotational angular positions from the A-phase, respectively. Each phase has two sets of separately wound windings around confronting stator teeth. They are 1) main winding, composed of four pole windings connected in series, and levitation windings from two confronting pole windings in serial connection.

When the main winding is activated with certain current, the magnetic flux density is weakened for air gap *a1* and enhanced for air gap *a2*, respectively. A superimposed magnetic field with force F_α is generated at the positive α direction. By alternation of the amount and direction of injection current from the levitation windings, a magnetic levitation force at the opposite α direction can be generated. Similarly, levitation force for positive and opposite β directions can be generated by regulation of current from perpendicular levitation windings. By implementation of proper feedback control algorithm for the rotor angular position, successful stable radial levitation can be achieved for any directions [10]. This method can be extended to B- and C-phase accordingly. Detailed introduction of operation principle can be found in [11-13].



(a) Winding scheme



(b) Flux distribution at 10 A
Fig.5 Winding scheme (a) and flux distribution

5 LEVITATION CONTROL SCHEME

At first stage, PID control algorithm can be implemented for both rotation and levitation. The overall control scheme is summarized as shown in Fig.6.

The control diagram includes the BSRM, the power drive circuits for the main windings and levitation windings, DSP controller, CPLD logic controller and PID controller. For convenience, the current for levitation windings are regulated with the current from main windings unchanged. Therefore the drive circuits for the main windings are the same as a common 12/8 SR machine. To achieve a stable levitation state, the inverter circuits are designed to be capable of providing bi-directional regulation current with a wide range. The CPLD unit is introduced the complementation of insufficient DSP logic units for the purpose of switch control. More results will be reported soon after the construction and control implementation of the prototype.

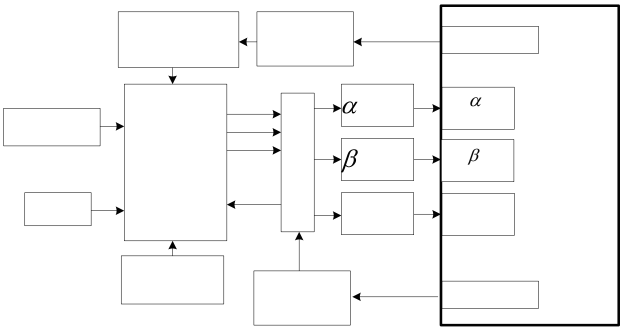


Fig.6 Control block diagram of BSRM

6 CONCLUSIONS

A new 2D rotary/propulsion bearingless SR motor is proposed in this paper. The total cost of the motor is low since there is no expensive material such as permanent magnets required. Furthermore, some special requirements of practical applications, such as high temperature working environment can be fulfilled naturally by using this motor as part of the motion system. The design of the 2D motor is derived from the idea of a planar switched reluctance motor previously constructed by the authors [8]. Extensive FEA simulations are performed for the rotary and propulsion part to ensure that they are magnetically decoupled.

The mechanical prototype of the proposed motor is under construction and the experimental results will be ready and reported soon. In conclusion, accurate position control of the 2D SR motor is new to literature and the proposed system introduced in this paper is beneficial to precision motion control industry.

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