A Rotary-Linear Switched Reluctance Motor

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Abstract—This paper aims to investigate, develop and fabricate a direct-drive, rotary-linear motor based on switched reluctance (SR) principle. The proposed system has the advantages of mechanically robust, simple structure and operation under hostile working environment. The finite element analysis (FEA) provides an intuitive and precise analysis of the proposed motor. The proposed machine is expected to find applications in high-precision manufacture field.

Keywords—direct-drive, switched reluctance, FEA

I. INTRODUCTION

Manufacturing of advanced electronic handheld products and components requires precise rotary and linear motion such as parts assembly, PCB drilling and component insertion, etc. To achieve precise rotary and linear motion most of the high-performance manufacturing machines use a rotary motor installed on a linear moving platform or rotary-to-linear mechanical couplings. Though this is the commonly used method, it has the disadvantages of complex mechanical structure, frequent mechanical adjustments, high manufacturing/maintenance cost, and low reliability [1].

In a direct-drive machine, the mechanical energy is directly performed onto the actuator or load, thus eliminating any mechanical couplers such as gears or belts for motion transformation. It has the advantages of fast response, high flexibility and the overall control system may have a simple structure [2]. Switched reluctance motor has never been a popular choice for high-precision and high-speed motion applications, because it is difficult to control and its output has high torque ripples. This is due to the fact that the actuator's characteristic is highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control. It was only until recent years which we see a general resurge of interest in the switched reluctance motor [3]. This was mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through complex control strategy". It must be stressed that most of these developments are directed towards general speed/torque control of rotary SR motors only.

This paper describes the development of a novel, high performance, direct-drive rotary-linear motion system for industrial manufacturing applications. The actuator is based on SR principle, and it aims to replace the traditional rotary-linear machines as a higher performance and lower cost alternative.

II. MOTOR STRUCTURE

The SR machine is a three-phase tabular motor and four-phase rotary machine combined together as shown in Fig.1. The rotor has a toothed structure to ensure appropriate flux path along the stators, airgap and the rotor and it as a uniform structure. The rotor has the degree-of-freedom in rotary and Z directions. To prevent the rotor from Y-axis movement, the rotor axis is tightly fixed in the motor shell with the rotor pin and ball screws to facilitate Z-axis movement and rotary motion only.

A. The propulsion motor

The propulsion motor is based on the "straightened-out-and-rolling" version of a 6/4 pole rotary switched reluctance motor, along the Z directions as shown in Fig.2. Two sets of 3-phase coil windings with wide magnetic teeth are employed on the moving platform. The propulsion winding is in series connection for each phase to obtain a balanced flux distribution on both sides of the propulsion stator, airgap and rotor. This arrangement ensures a larger propulsion output performance [4]. The wide magnetic teeth ensure that there is little force coupling between the two motion axes. The distance between each propulsion stator is selected so that when one phase is fully aligned with the rotor rod, the other two propulsion stators

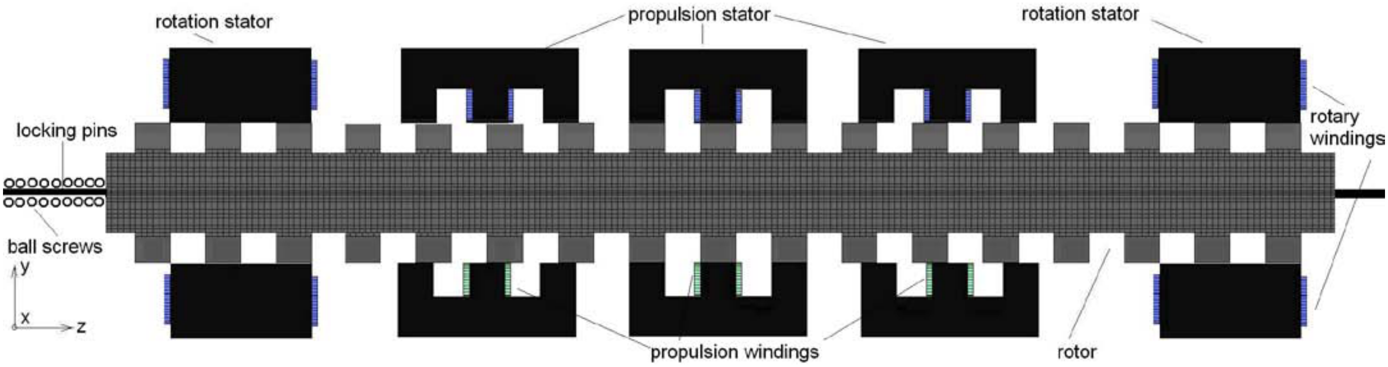


Fig.1: Layout of the 2D motor

are in mis-aligned position so that when one phase moves along the Z direction when activated, the other one will move in the opposite Z direction being excited. This configuration conforms to a three-phase linear SR motor to active-stator-passive-mover structure [4]. The arrangement has the following features and advantages [5],

- Individual mover slot with coil simplifies winding scheme thus reduce manufacture cost of the moving platform.
- Zero mutual inductance can be achieved between adjacent movers with flux-decoupled windings.
- Long travel distance can be accomplished easily with the combination of longitudinal tracking supports.

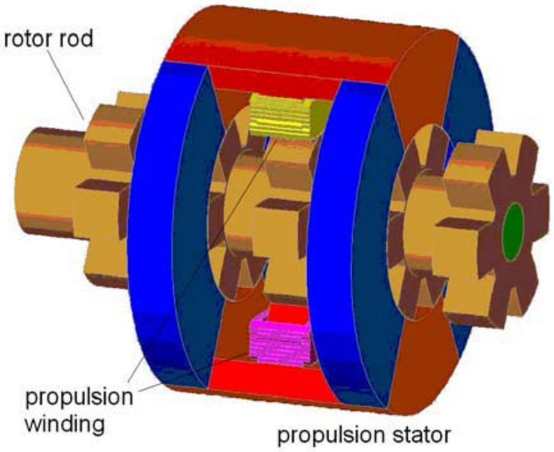
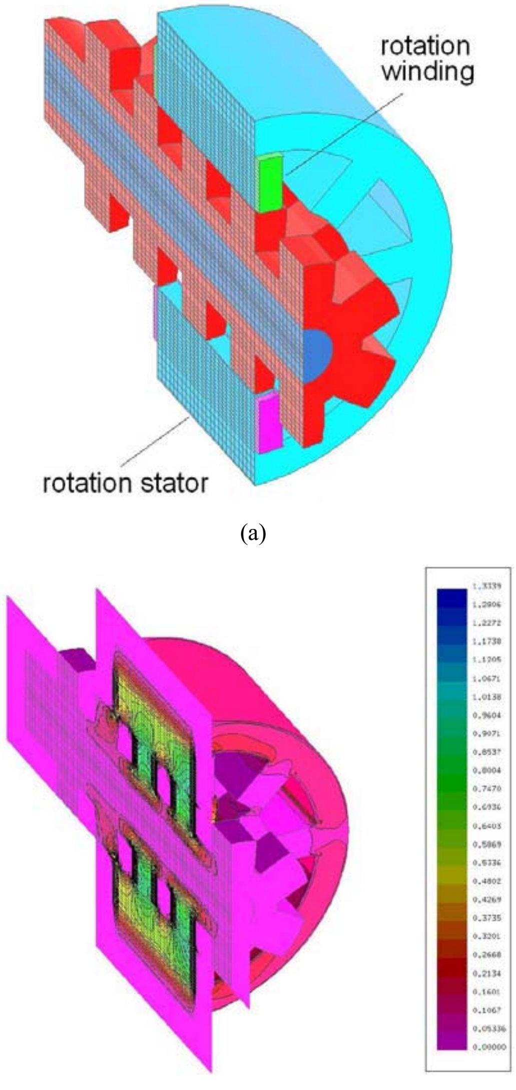


Fig.2 Structure of propulsion stator in one phase

B. The rotation motor

The rotation motor has the common 6/4 pole rotary switched reluctance motor structure. Two rotation stators are installed on each end of the rotating rod for rotary balancing. The stack length of the stator is carefully designed as a multiple of rotor pole-pitches for the production of larger torque and to ensure uniform flux from the rotor rod. As shown in Fig. 3 (b), when the rotary winding is activated, flux distribute along the stator, rotor and the two airgap regions in between. If the rotor moves a certain distance along the Z direction, the rotation stator partly overlaps the pair of stator teeth moving in and the teeth moving out. However, since the stack length is multiple of the rotor pole-pitch, the overlapping area for flux distribution remains unchanged. Therefore the flux distribution is almost the same under different relative stator and rotor positions.



(a)

(b)

Fig.3 Structure of the rotary motor (a) and flux distribution (b)

III. 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].

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

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

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

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.

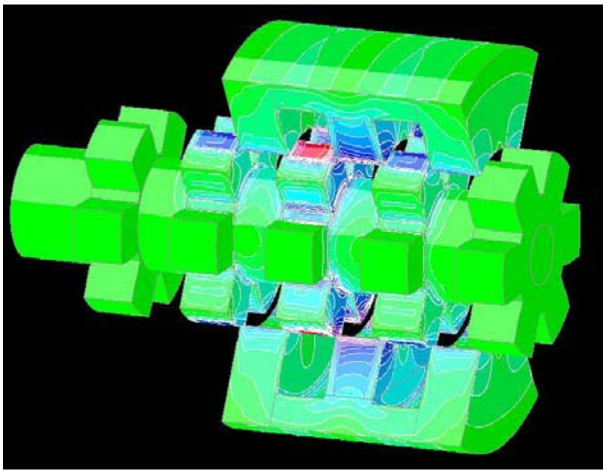
Force is calculated as the change of co-energy W_{co} according to displacement as follows,

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

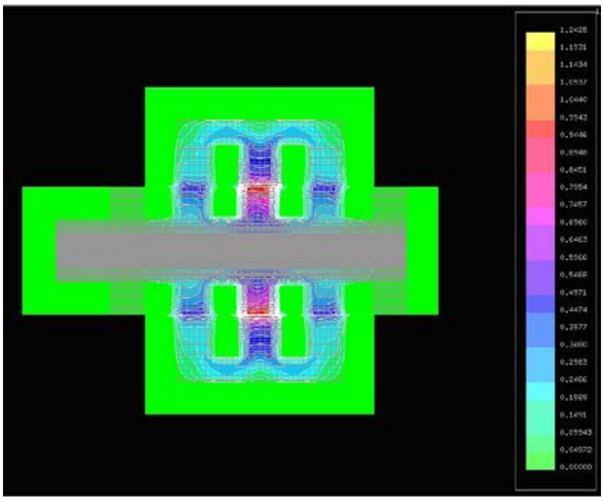
IV. THE FINITE ELEMENT SIMULATION

Since the performance of the rotary motors can be found in many articles [3], to further predict the electromagnetic characteristics of the motor, a series of finite element analysis has been conducted for propulsion movement.

Since each phase of the propulsion motor has the same dimensions and ratings, only one phase is taken into consideration as shown in Fig.5 (a) and (b) for 3D and 2D FEA respectively, when the stator teeth misaligns with the rotor rod. It can be concluded that flux distributes along the each side of the rotor teeth, stator teeth and the two airgap regions only.



(a)



(b)

Fig.5 3D and cross sectional flux distribution (a) and (b)

To further predict the performance of the propulsion motor, force is calculated under different current and positions in half-pole pitch (9 mm) as shown in Fig.6. It can been seen from the simulation result that the three-pair stator teeth arrangement provides a smooth force output under low levels of current excitations.

V. CONCLUSIONS

A new type of two-dimensional, rotary-linear 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. FEA simulations are performed for the motor to predict the motor performance. 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 is beneficial to precision motion control industry.

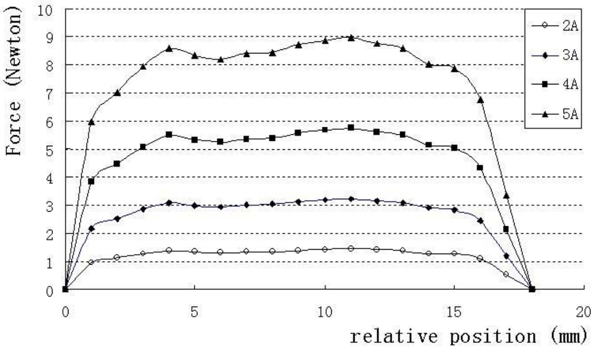


Fig.6 Force output of propulsion phase

VI. ACKNOWLEDGEMENT

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