Investigation of a rotary-linear Switched Reluctance motor

J.F Pan, N.C.Cheung, Guang-zhong Cao

Abstract—A novel direct-drive rotary-linear switched reluctance motor (RLSRM) is proposed. The motor has the advantages of robust mechanical structure, low manufacture cost and capability of operation under hostile environments. Simulation tools such as finite element analysis (FEA) are applied for the verification of motor performance and corresponding experiments are carried out to testify the simulation results. The authors expect that the innovative actuator design can be applied in industrial applications that require both rotary and linear motions.

Index terms—switched reluctance, rotary-linear motor, FEA

I. INTRODUCTION

IN modern industry, high-precision rotary and linear movements are highly demanded such as component insertion, PCB drilling, etc. The traditional method is to use two rotary motors with linear mechanical translators stacked on each other. It has the disadvantages of accumulated error, high cost and frequent maintenance.

The authors propose an integral direct-drive rotary-linear machine based on switched reluctance principle. Through this paper, the design methodology and a thorough investigation is performed.

Design and construction of the motor are introduced in Section II. Mathematical formulations are provided in Section III. In Section IV, finite element simulations are performed. Corresponding experimental results are given in Section V to verify the FEA results. Concluding remarks are presented in Section VI.

II. MOTOR DESIGN AND CONSTRUCTION

By "wrapping" the planar motor previously studied [1] along the two edges together with the moving platform, a cylindrical machine would be formed capable of both rotary and linear motions. Considering manufacture simplicity, the prototype applies the linear stroke within one pole-pitch and rotation as a typical 6/4 switched reluctance machine. Fig.1 shows the overall structure of the motor and Table I illustrates the electrical and mechanical parameters of the motor.

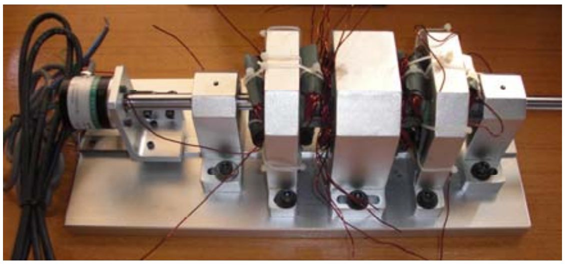

Fig. 1. The motor

TABLE I

ELECTRICAL AND MECHANICAL PARAMETERS

Parameter	Value
rotor/stator mass	9.5 N/64.5 N
size of stator base	34.5 mm×14 mm
length of rotor rod	33 mm
number of turns per phase (rotary)	40
number of turns per phase (linear)	60
pole-pitch (linear/rotary)	10 mm/60°

A. *The Rotor*

The rotor rod has a uniform silicon-steel stacking structure along the rotation axis. As shown in Fig.2, the stacking utilizes laser soldering instead of long screws to avoid mechanical destruction such as holes and improve the magnetic circuit for a better output performance.

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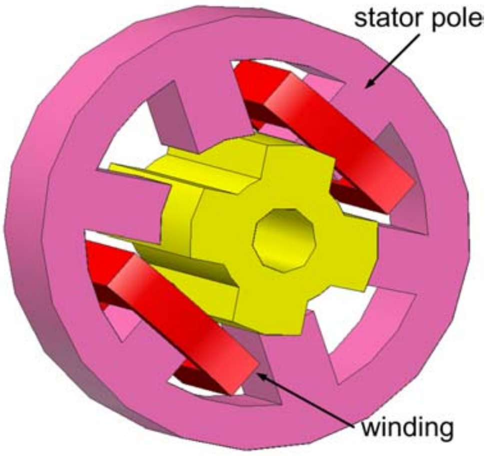
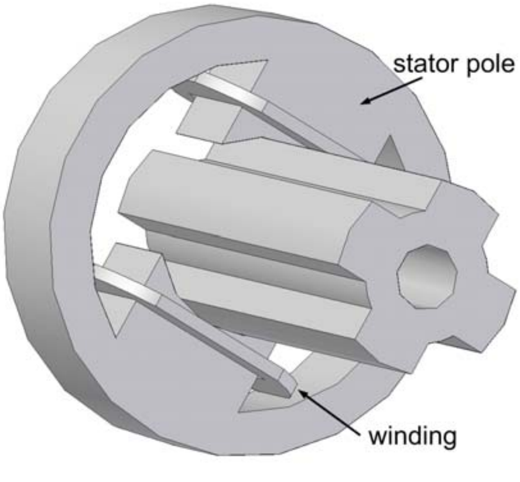
Fig. 2. The rod

B. *The Stator*

The stator is composed of three magnetic rings wound with windings as shown in Fig.3. The rotary ring has the typical 6/4 SR motor structure with three-phase windings serially connected [2]. Two linear propulsion rings are installed on both sides of the rotary ring to balance translation forces. Both rings have two poles facing oppositely with windings connection in series.



(a) the rotation ring



(b) the linear propulsion ring

Fig. 3. The stator rings

III. MATHEMATICAL FORMULATIUON

For both rotary and linear part, the voltage balancing equation can be characterized as [3],

$$\begin{aligned} u_k(t) &= R_k i_k(t) + \frac{d\lambda(\theta,t)}{dt} \\ &= R_k i_k(t) + \frac{\partial L_k(\theta,t)}{\partial t}\cdot i_k(t) + L_k(\theta,t)\frac{\partial i_k(t)}{\partial t} \end{aligned} \tag{1}$$

where u_k and i_k are the input voltage and current for the *k*th coil (k=1-3). R_k , λ are winding resistance for the *k*th coil and flux-linkage established during excitation.

Torque T_e is presented as,

$$T_e = J\frac{d^2\theta}{dt^2} + K\frac{d\theta}{dt} + T_L \tag{2}$$

where J is moment of inertia, K is friction coefficient and T_L , load torque.

The general representation of force production for any one ring can be described as [4],

$$F_i = \frac{\partial W_{co}}{\partial x} \tag{3}$$

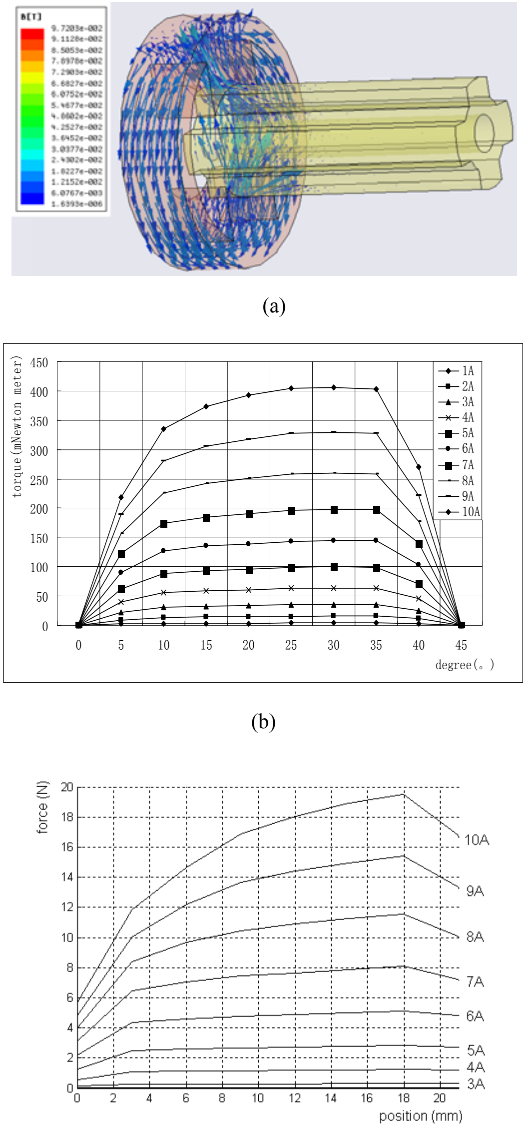
where force *F* for the *i*th linear ring is calculated as the change of co-energy W_{co} according to displacement *x*. If the current is low and the force is generated under unsaturated region,

$$F_i = \frac{1}{2}\frac{\partial L_i}{\partial x} I_i^2 \tag{4}$$

where L_i is the inductance of *i*th ring and force is approximately considered as half of change of inductance with *x* multiplied by current squared, regardless of current direction.

IV. CHARACTERISTIC VERIFICATION

To precisely represent the actuator, three dimensional finite element models are constructed using Ansoft Maxwell® software package for torque and force calculations. As shown in Fig.4 (a) the special flux circulation path, a non-linear force relative to position can be predicted. Torque is calculated according to different current excitations with respect to relative positions from the rotor to the stator as shown in Fig. (b). Torque results also show dominant saturation effect at 4A. As shown in Fig.4 (c), due to end effects, the force does not reach zero at fully non-overlapping positions and force curves clearly demonstrate a non-linear relationship between the force and the relative positions according to different current levels. Therefore a proper linearization scheme will be included for position control of the linear part in control algorithms.



(a)

(b)

(c)

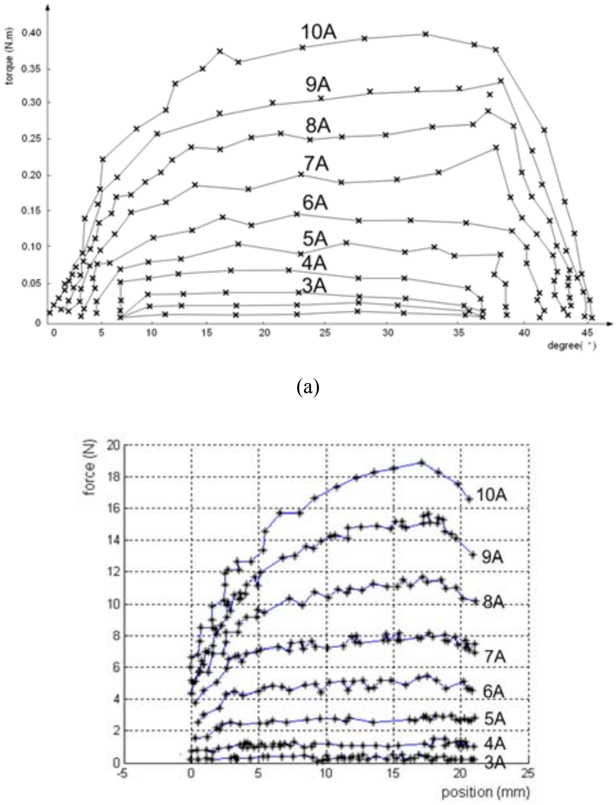
Fig. 4. FEM results of (a) flux path of linear part, (b) torque and (c) force calculation from FEM

V. EXPERIMENTAL RESULTS

To verify the simulation results from FEM and fully observe motor performance in real operations, experiments on torque and force are implemented with a dSPACE DS1104 controller card. Reference current is generated by the controller card and position feedback from the rotary and linear encoder is collected through digital-to-analog converters (DACs) and analog-to-digital converters (ADCs). The controller card is responsible for encoder output collection and to provide a designated current command to the current drivers.

Torque and force measurement is conducted by a torque and a force gauge. Angle and position information are fed back to the PC from the optical rotary and linear encoders. The various input current excitations are provided with a generalized current driver. Signals are sampled consequently into the PC for further data processing.

As shown in Fig.5 (a), torque value reaches peak value at a relative degree of 35° , which corresponds with the FEM results. The force measurement results are shown in Fig.5 (b). Compared with the simulation results from FEM, the measured data have good correspondence. The difference under the same position and current excitation derives from static friction and measurement errors.



(a)

(b)

Fig. 5. Torque and force measurement results

VI. CONCLUSION

A novel rotary-linear machine based on SR principle is presented in this paper. The motor is capable of both rotation as well as linear propulsion. Simulation and experimental results verify the characteristics of the motor and prove the non-linear characteristics existed in this machine. For further study, the coupling effect between the rotary and linear part between will be fully explored and a proper control algorithm should be introduced in later development. It is expected the device to be applied in industry for high-precision control applications.

VII. REFERENCES

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VIII. BIOGRAPHIES

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