Performance Analysis of an Integrated Rotary-linear Machine with Coupled Magnetic Paths

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***Abstract*—An integrated rotary-linear machine based on switched reluctance (SR) principle is investigated. The performance of the motor is inspected by finite element methods (FEM), especially for the coupled magnetic paths. Numerical calculation results are verified by experiments. The simple decoupling algorithm for the independent position control of rotary and linear axis is proposed. Combined with proportional derivative integral (PID) algorithm, the motor is capable of high-precision rotary and linear position tracking with steady error within 0.3° and 10 μm, respectively.**

***Index Terms*—rotary-linear machine, FEM, position control.**

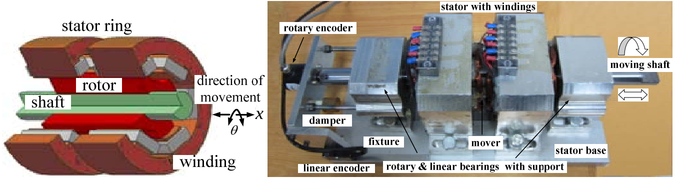
I. INTRODUCTION

In industry, two-dimensional (2D), high-precision rotary-linear motions are widely required in various applications such as component insertion, printed board printing (PCB) drilling, etc. [1]-[3]. In this paper, an integrated rotary-linear motor based on switched reluctance (SR) principle is proposed with performance prediction and decoupling control. Compared with other type of rotary-linear motors [4], this machine has the following advantages,

1. least winding arrangement and simple winding scheme with coils mounted on the stator
2. robust mechanical structure for the doubly salient motor topology
3. low overall system and production cost with isolated sensing mechanism
4. good heat dissipation with open motor structure

II. MACHINE CONSTRUCTION

By adding an extra identical winding and extension of the length of the rotor, the machine with two degrees of freedom can be achieved as shown in Fig.1 (a). It is composed of a rotor and two identical stator rings and windings at zero phase shift, stator base, and rotary-linear ball bearings on the fixture. The stator rings conform to the typical 6/4 SR motor topology. Instead of integrated fiber optic switches for angular detection [3], a rotary optical encoder is concentrically mounted on the shaft. A linear magnetic encoder is installed for linear stroke measurement. Fig.1 (b) shows the prototype of the machine. Major specifications are listed in Table I.



(a) (b)

Fig.1. Machine schematic (a) and prototype (b)

TABLE I
MAJOR MACHINE SPECIFICATIONS

Parameter	Value	Parameter	Value
Stator mass	5 Kg	Rotor mass	1.5 Kg
Stator diameter	120 mm	Rotor stack length	120 mm
Stator yoke	14.5 mm	Rotor diameter	60 mm
Stator pole arc width	22 mm	Rotor pole arc width	22 mm
Stator pole height	15 mm	Rotor pole height	7.5 mm
Stator stack length	30 mm	Rotor yoke	10 mm
air gap	0.4 mm	Number of turns per phase	150
Pole-pitch (linear/rotary)	10mm/ 60°	Encoder resolution (linear/rotary)	1 μm/ 0.144°

III. THEORETICAL BACKGROUND

The rotary-linear machine is composed of a coupled rotary and linear electromechanical system. From the rotary part with any of the stator ring, the machine can be characterized as,

$$T = J\ddot{\theta} + K\dot{\theta} + T_L \,. \tag{1}$$

where T is generated torque, J is moment of inertia, K is rotational friction coefficient. θ is angular position and T_L is the load torque. From the linear motion part,

$$F = M\ddot{x} + B\dot{x} + F_L \,. \tag{2}$$

where F is generated force, M is mass of the moving shaft, B is linear friction factor. x and F_L are linear position and thrust force, respectively. In the linear region, torque and force can be approximated as,

$$\begin{cases} T = \frac{1}{2}\cdot\frac{\partial L_1}{\partial\theta}\cdot i_1^2 + \frac{1}{2}\cdot\frac{\partial L_2}{\partial\theta}\cdot i_2^2 \\ F = \frac{1}{2}\cdot\frac{\partial L_1}{\partial x}\cdot i_1^2 + \frac{1}{2}\cdot\frac{\partial L_2}{\partial x}\cdot i_2^2 \end{cases} . \tag{3}$$

where L and i are inductance and current, respectively. It is clear that torque and force generation are both dependent on phase current of the stators. Therefore the magnetic paths are nonlinear and highly coupled.

IV. PERFORMANCE ANALYSIS

Three-dimensional (3D) finite element model has been constructed for performance prediction. Flux distribution on the cross-section of the x-θ plane can be found in Fig.2 (a). Calculation of linear force output profile for the fully aligned angle and torque profile v.s different angular positions of any one phase be found in Fig.2 (b) and (c), respectively.

V. DECOUPLING SCHEME

The decoupling method is described as the following steps.

1) Current from each coil can be treated as the sum of components contributive to rotary and linear motion. Fig.2 (d) shows the torque profile generated from the component of linear motion from any stator ring (2.5 A), denoted as *Al*, *Bl* and *Cl*, respectively. For effective decoupling control from the rotary and linear axis, the following equation must be satisfied as,

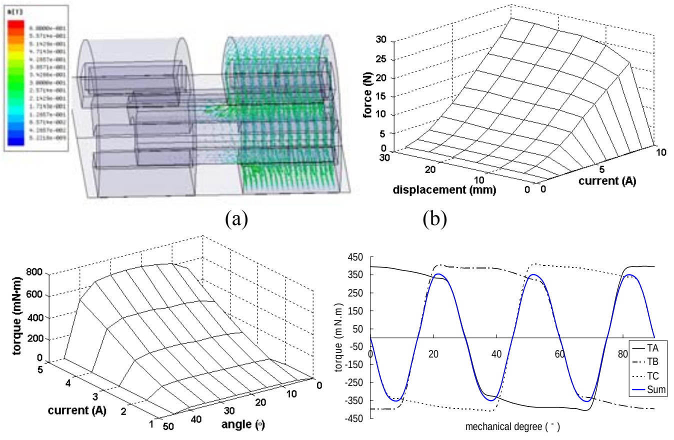
$$\begin{cases} T(Al)+T(Bl)+T(Cl)=0 \\ Al+Bl+Cl=d \end{cases}. \qquad (4)$$

where d is the required total current reference for linear motion calculated by the controller.

2) From Fig.2 (d), it is clear that the angular region can be divided into six segments in a mechanical rotating angle period as follows,

$$\begin{cases} (0^\circ-10^\circ\,\&\,80^\circ-90^\circ), Cl=0 \\ (10^\circ-20^\circ), Bl=0 \\ (20^\circ-40^\circ), Al=0 \end{cases} \text{and} \begin{cases} (40^\circ-50^\circ), Cl=0 \\ (50^\circ-70^\circ), Bl=0 \\ (70^\circ-80^\circ), Al=0 \end{cases}. \qquad (5)$$

3) The decoupling mechanism can be derived by combining (4) and (5).



(a) (b)

(c) (d)

Fig.2. (a) Flux distribution of mutual magnetic path (b) linear force profile (c) torque profile and (d) torque generation from linear current component

VI. EXPERIMENTAL VERIFICATION

To verify simulation results from FEM and fully investigate the motor performance, measurement for force and torque output are carried out. The overall experimental setup can be found in Fig.3.

A. *Torque and Force Measurement*

As shown in Fig.4 (a) the measured torque data, it can be found maximum torque value is 0.68 N·m, which corresponds to FEM results. Compared with FEM simulation, the measured force data have good correspondence as shown in Fig.4 (b).

B. *Control Scheme*

Based on the above analysis, the overall control schematic can be found in Fig.5. With the decoupled algorithm, the simple PID controller can be employed for independent angular and linear position control. As shown in Fig.6 the position control response, the motor is capable of tracking command signals precisely with rotary and linear steady error of 0.3° and 10 μm, respectively.

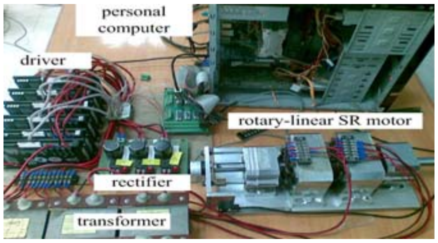
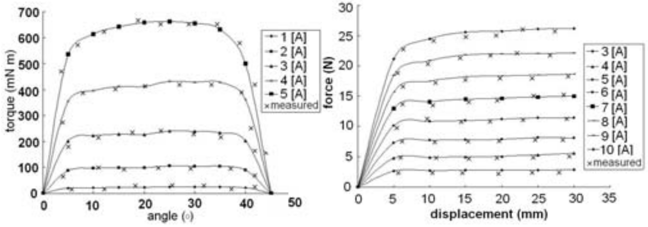


Fig.3 Experimental setup



(a) (b)

Fig.4. (a) Torque measurement data vs FEM calculation and (b) force measurement data vs FEM calculation

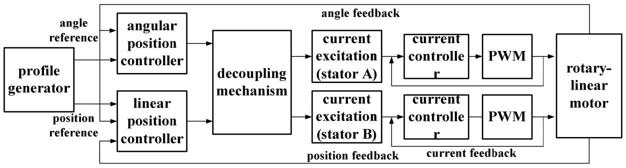


Fig.5 Control schematic

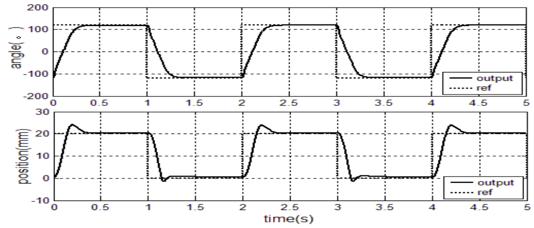


Fig.6. Position control performance for rotary and linear motion

VII. CONCLUSION

A direct-drive rotary-linear machine based on SR principle is discussed. The isolated sensing mechanism makes the control system simple and robust. Motor performance is investigated by FEM and the results correlate with those from the experimental results. The simple PID control scheme with the decoupled algorithm is effective for independent control of rotary and linear axis, respectively.

VIII. ACKNOWLEDGEMENT

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