

# Flux Characteristics Analysis of a Single-phase Tubular Switched Reluctance

## Linear Motor (Mon-Af-Po1.04)

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### Introduction

This paper analyzed the flux characteristics of a single-phase tubular switched reluctance linear motor (TSRLM) based on magnetic equivalent circuit (MEC) method. The single-phase TSRLM is divided into five different parts, which are the teeth of the stator, the yoke of the stator, air gap, the teeth of the rotor, and the yoke of the rotor. The reluctance of every part is expressed in analytical formulas at five special mover positions. The flux linkages at five special mover positions are calculated by magnet tube method and Gauss-Seidel iteration method which takes the saturation into consideration. A high order Fourier series is used to map the nonlinear relationship between flux linkage, current and mover position with the flux linkage data calculated by MEC method. The calculated flux linkage is consistent with 3D finite element method (FEM) and experimental results. The dynamic and static performance of the simulation utilized with MEC method are consistent with those in experiments, which verifies the accuracy of the MEC method proposed in this paper.

### Structure and Operating Principle

#### Structure

The single-phase TSRLM consists of two main parts, which are a stator and a mover. The bread type winding is embedded in the slot of the stator, which can improve the coil factor and decrease the end effect. Three mover teeth rings are uniformly distributed on the mover yoke sleeve. The stator sleeve, the mover teeth rings and the mover yoke sleeve are made up with silicon steel, 50DW470.

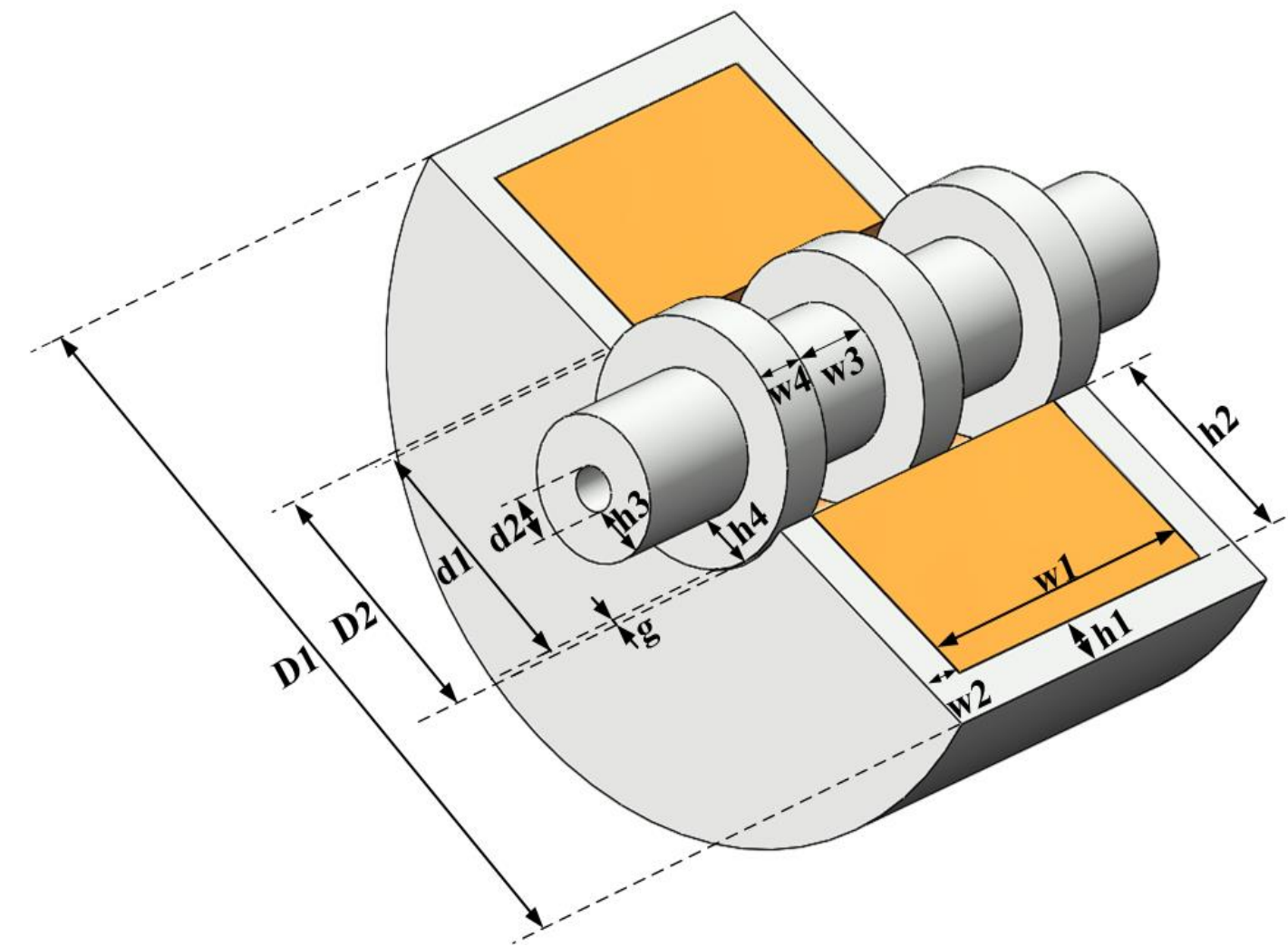


Fig. 1. Dimensions of single-phase TSRLM

#### Operating Principle

When the bread type winding embedded in the stator slot is energized, it can produce flux linkage, which can form a closed loop by passing the mover teeth rings, the rotor yoke sleeve, air gap, the stator teeth and the stator yoke. When the magnetic field lines twisted, it generates magnetic forces to drive the mover reciprocating in axial direction. The stroke of the motor proposed in this paper is from -5mm to 5mm.

### Flux-linkage Calculation

In order to calculate the flux characteristics of the single-phase TSRLM, magnetic equivalent circuit can be constructed with the help of the distribution of magnetic field lines in Fig. 2. The magnetic field lines pass through the mover teeth rings, air gap, the teeth of stator, the yoke of stator, respectively, and finally return to the mover, which forms a closed loop. The magnetic equivalent circuit is shown in Fig. 3. It consists of the stator teeth reluctance  $R_{sp}$ , the stator yoke reluctance  $R_{sy}$ , the air gap reluctance  $R_g$ , the mover teeth reluctance  $R_{rp}$ , the mover yoke reluctance  $R_{ry}$  and magneto motive force  $F$ . They are all connected in series.

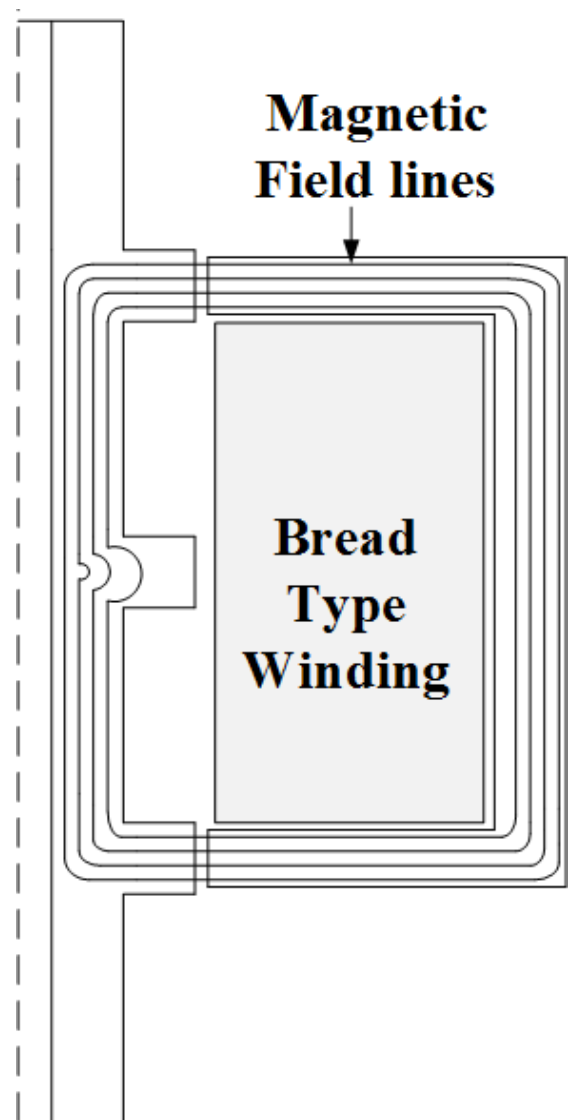


Fig. 2. Distribution of magnetic field lines at aligned position

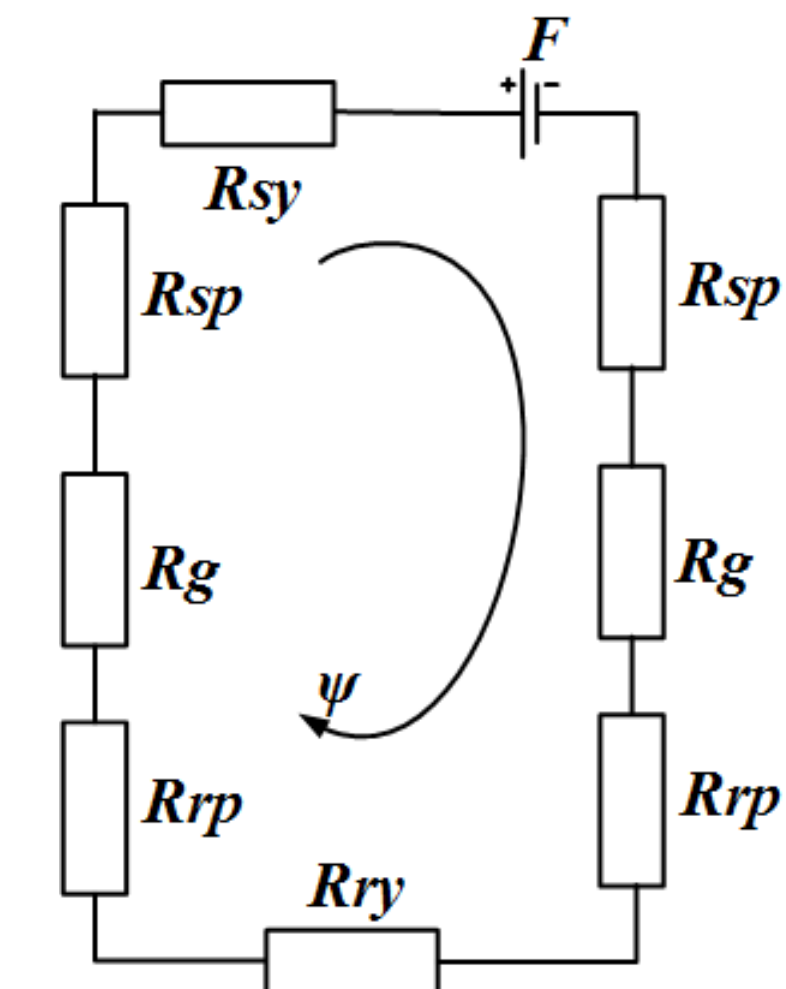


Fig. 3. Magnetic equivalent circuit at aligned position

The flux characteristics of the single-phase TSRLM at different mover positions can be calculated with flux tube method. Five special mover positions are chosen to analyze the flux characteristics of the single-phase TSRLM. The position  $x_a$  is the centerline of stator teeth aligned with the centerline of mover teeth. The position  $x_{1/4}$  is the stator teeth aligned with the mover teeth at  $w_4/4$ ,  $w_4$  is the width of mover teeth. The position  $x_{1/2}$  is the stator teeth aligned with the mover teeth at  $w_4/2$ . The position  $x_{3/4}$  is the stator teeth aligned with the mover teeth at  $3w_4/4$ . The position  $x_u$  is the critical misalignment position of the stator teeth and mover teeth.

Table I GEOGRAPHIC PARAMETERS IN THE TSRLM

Parameters of the motor	Dimensions
The outer radius of the stator $D_1$	63.0mm
The inner radius of the stator $D_2$	20.0mm
The outer radius of the rotor $d_1$	19.6mm
The inner radius of the rotor $d_2$	3.6mm
The thickness of the stator yoke $h_1$	4.0mm
The depth of the stator slot $h_2$	17.5mm
The width of the stator slot $w_1$	31.0mm
The width of stator tooth $w_2$	4.0mm
The thickness of mover yoke $h_3$	4.0mm
The depth of mover slot $h_4$	4.0mm
The width of mover slot $w_3$	12.5mm
The width of mover tooth $w_4$	5.0mm
The thickness of air gap $g$	0.2mm
The lamination thickness of mover $L$	65.0mm
The turns of winding $N_{ph}$	124

### Simulation and Experiments

The nonlinear model of the single-phase TSRLM is constructed with simulator in Matlab/Simulink. The nonlinear relationship between flux linkage, current, and mover position is shown in Fig. 4. The prototype of TSRLM put forward in this paper is shown in Fig. 5, whose geographic parameters are listed in Table I. The flux linkage of the single-phase TSRLM in given position and given current is calculated with MEC method proposed in this paper. The comparison of magnetic curves of the three is shown in Fig. 6. It can be seen from Fig. 6 is that the MEC method proposed in this paper is consistent with the 3D FEM results and experimental results, which takes the saturation into consideration.

The simulated and tested current and voltage waveforms of the single-phase TSRLM in different speeds are shown in Fig. 7. The static thrust comparison of the MEC method and the experiment result is shown in Fig. 8. Three specific currents are chosen to compare the generated static thrust, which are 2A, 4A, and 6A.

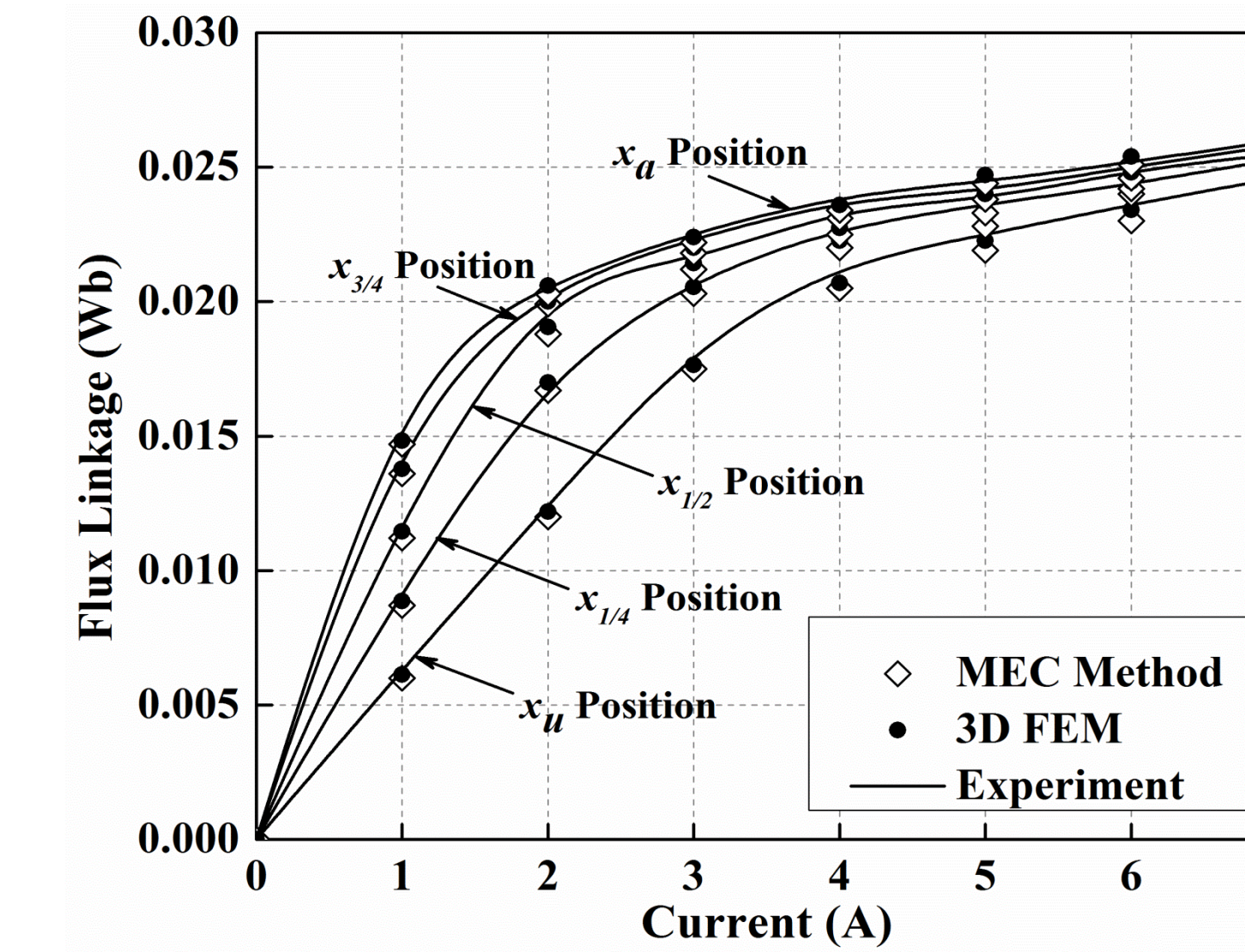


Fig. 6. Comparison of flux linkage in five positions

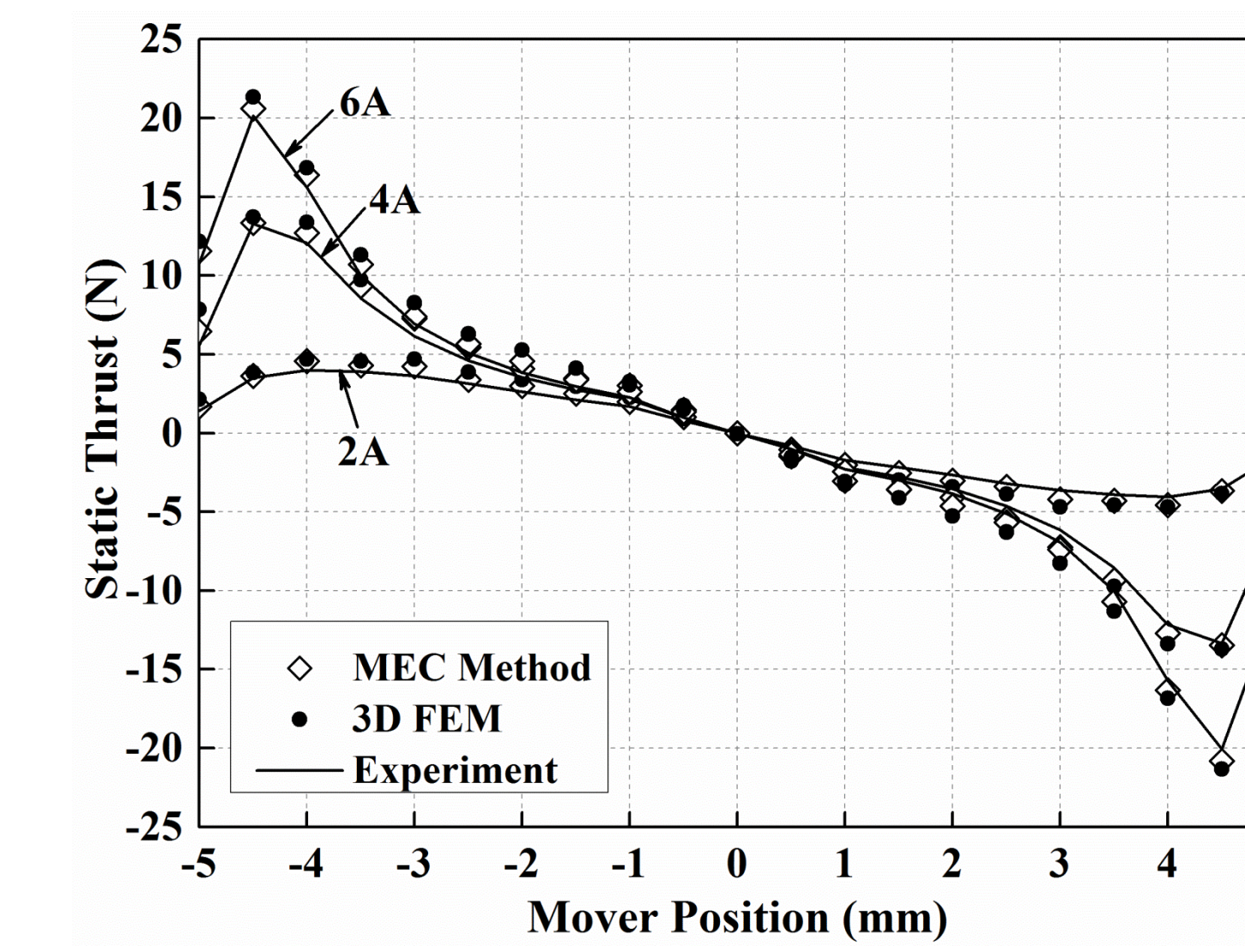


Fig. 8 Static thrust comparison of MEC and experiment

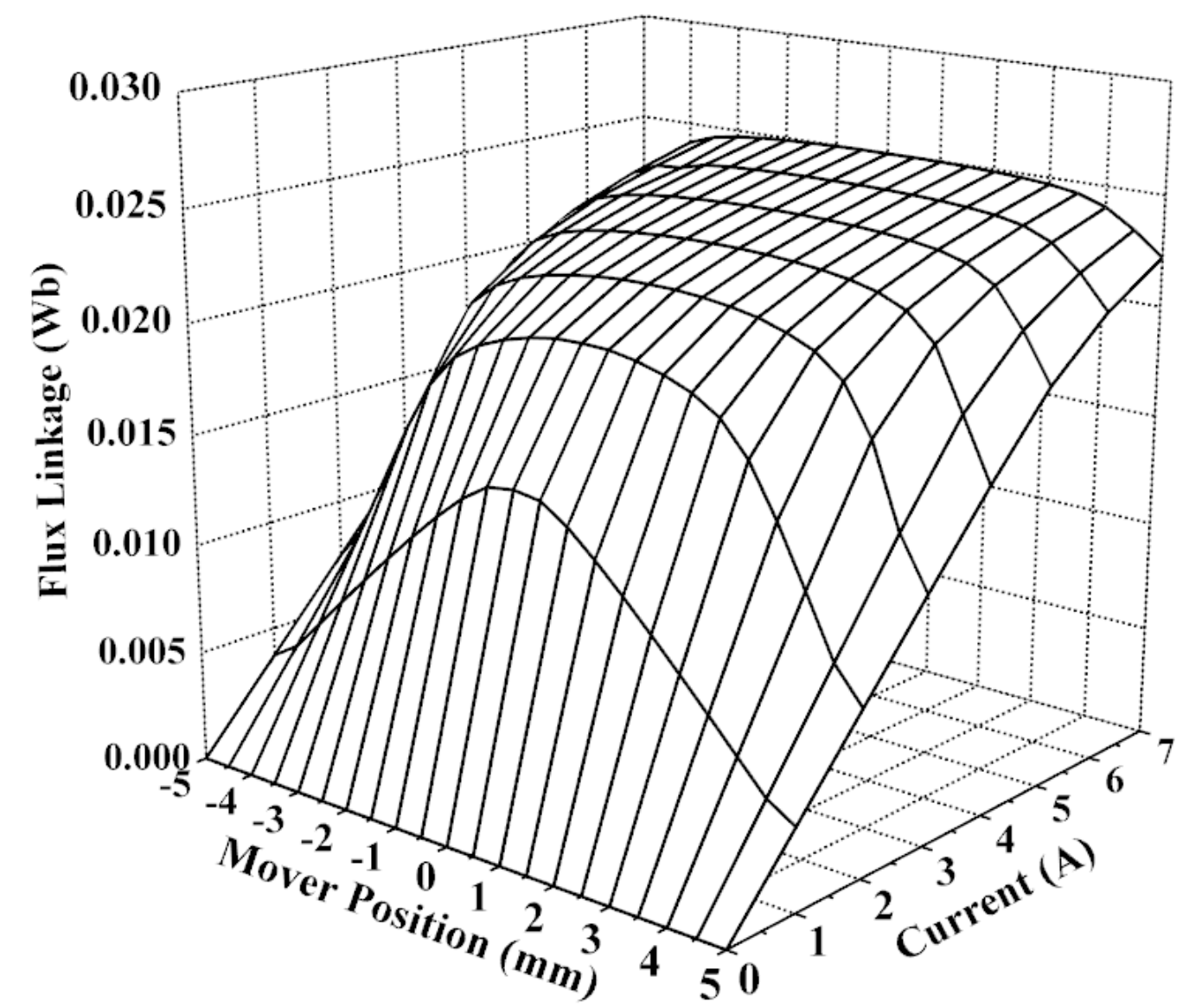


Fig. 4. Flux linkage of the single-phase TSRLM

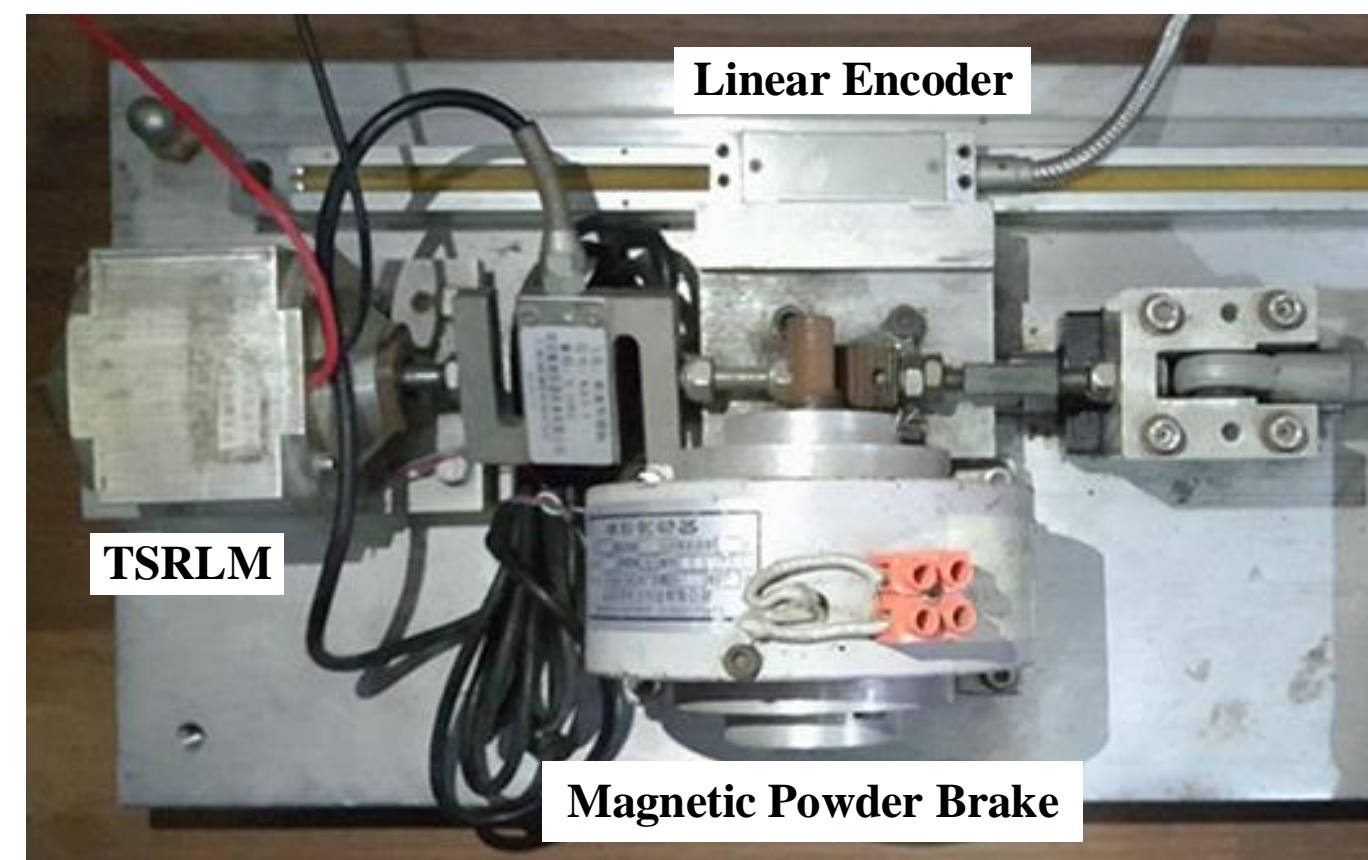


Fig. 5. prototype of the experimental platform

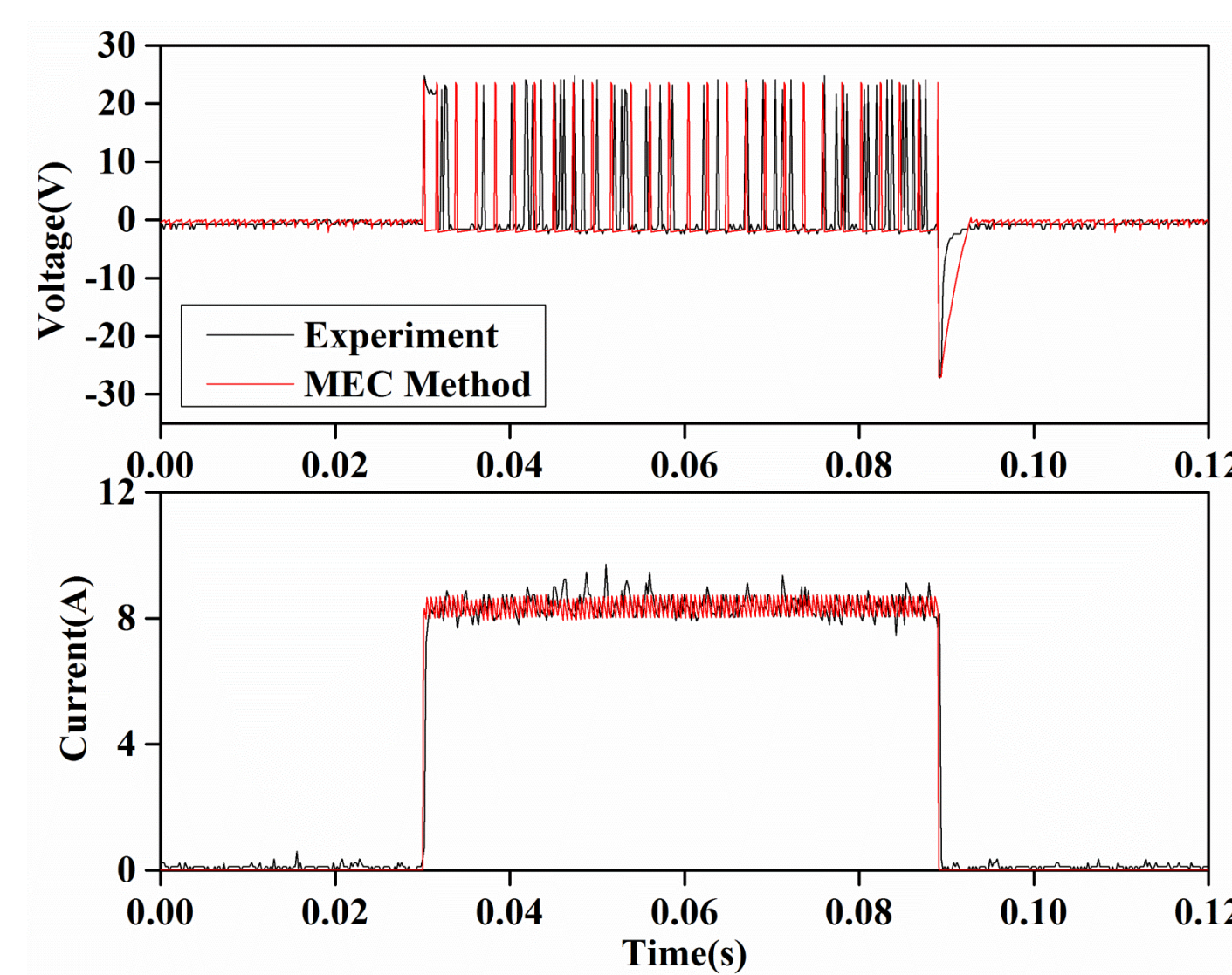
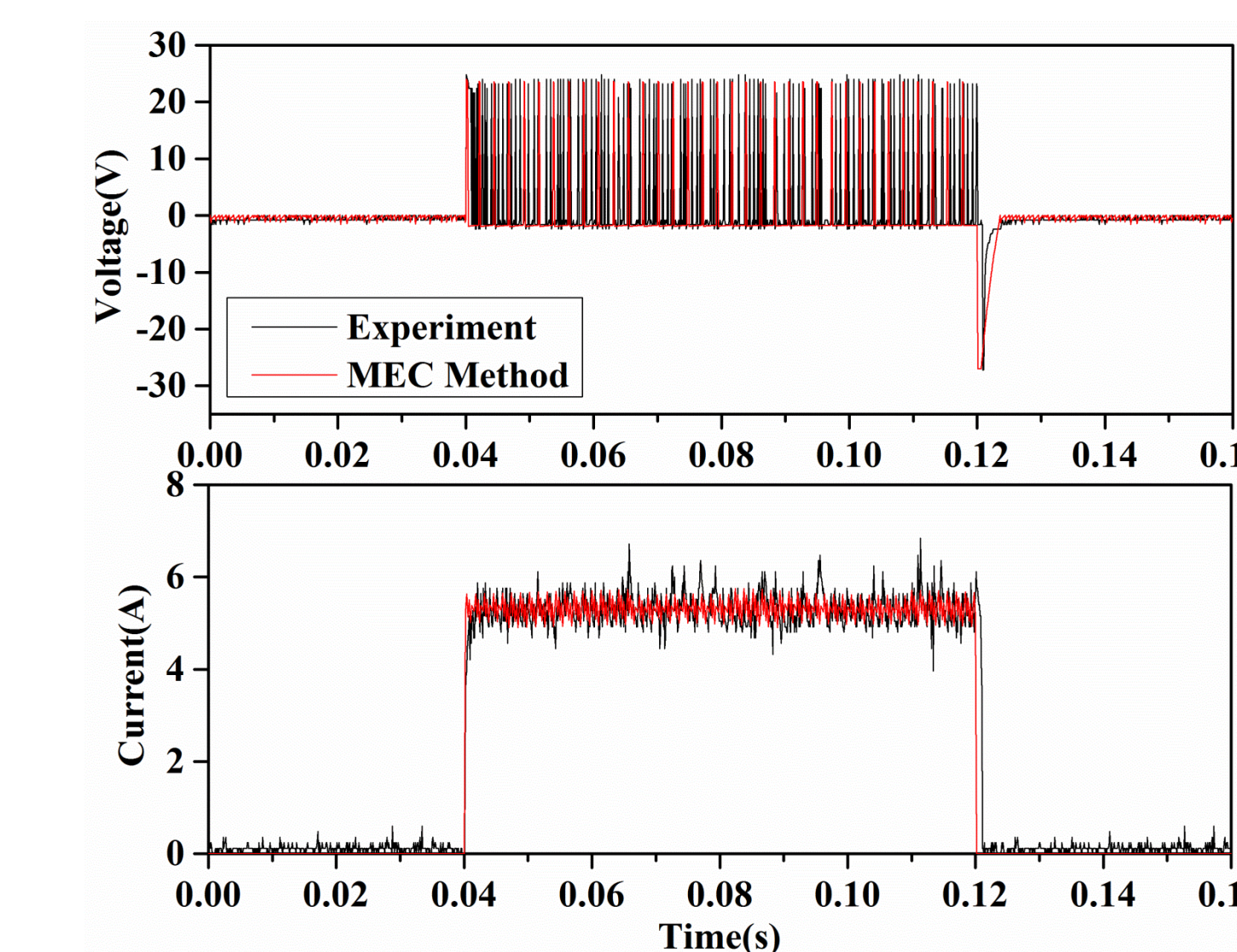
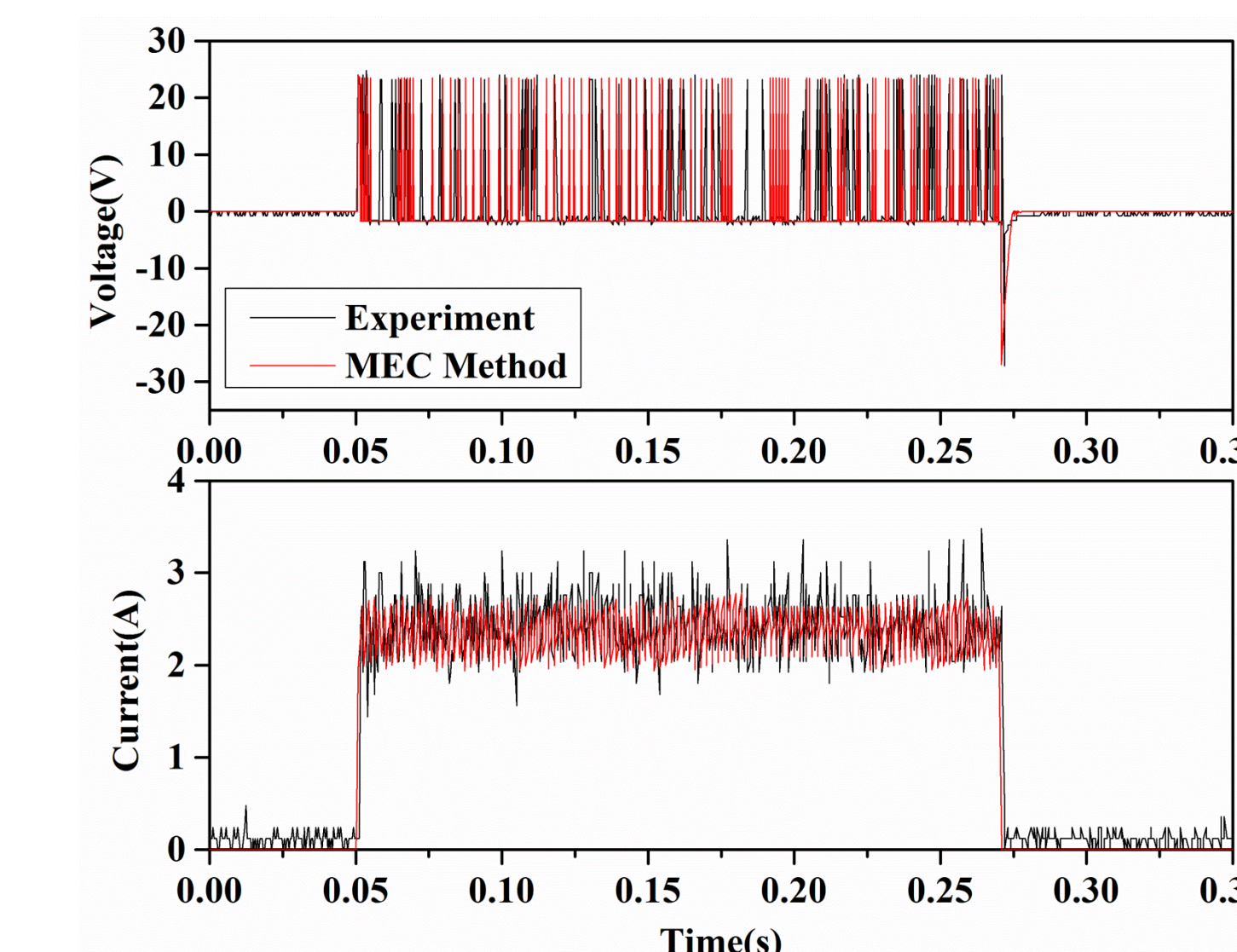


Fig. 7. The voltage and current waveforms in different speeds. (a) 2Hz (b) 6Hz (c) 10Hz

### Conclusions

- ❖ A MEC method is put forward to obtain the lux linkage of a single-phase TSRLM at five special mover positions which takes the saturation of material into consideration.
- ❖ The flux linkage is compared with the 3D-FEM results and experimental results, thus the correctness of the MEC method is validated.
- ❖ The MEC method is consistent with the 3D-FEM results and experimental results.
- ❖ The dynamic and static performance of the single-phase TSRLM verifies the validity of the MEC method.