# Mon-Af-Po1.04-15 [45] Study on high efficiency permanent magnet linear synchronous motor for maglev

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## Background

The **mid-and-low speed maglev train** driven by linear motor is becoming more and more common in modern urban rail transit because of its great traction, starting fast, low noise, small vibration, small turning radius, strong climbing capability. There are different views on which kind of traction motor is better for driving the mid-and-low speed maglev train. But **high efficiency, low cost**, and high safety factor are the main pursuits.

## Objectives

- Finding the optimal slip frequency of the linear induction motor for driving the typical mid-and-low speed maglev train.
- Improving the traction efficiency of the coreless Halbach permanent magnet linear synchronous motor for driving the typical mid-and-low speed maglev train.
- Determining which kind of linear motor is better for driving the mid-and-low speed maglev train.

## Conclusion

- The optimal slip frequency of the linear induction motor for driving the typical mid-and-low speed maglev train running uniformly at 140 km/h is 19 Hz.
- The optimal angle between the magnetization direction of two adjacent permanent magnets of the coreless Halbach permanent magnet linear synchronous motor is 45°.
- The traction efficiency of the coreless Halbach permanent magnet linear synchronous motor is improved through changing the cross-sectional shape of the conductor.
- The coreless Halbach permanent magnet linear synchronous motor is better for driving the mid-and-low speed maglev train.

## Coreless Halbach PM-LSM

### Different magnetization direction

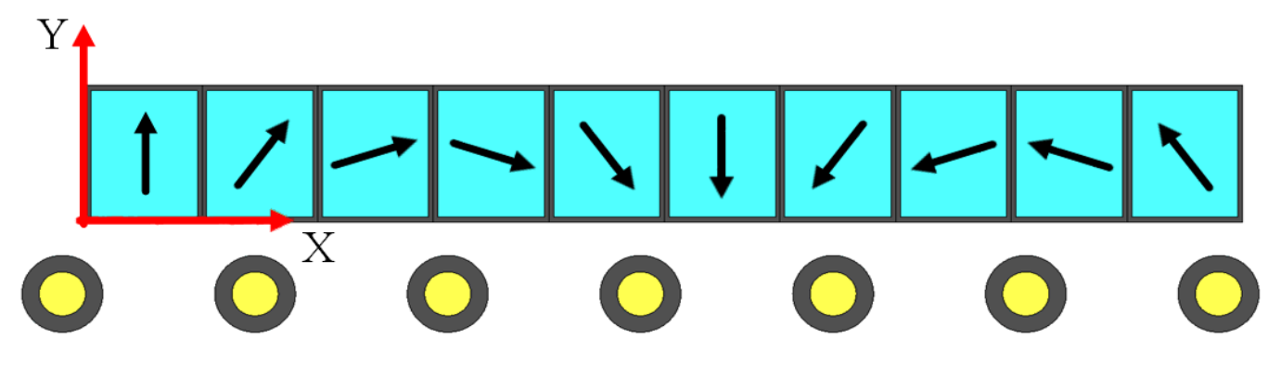
Every linear motor of the mid-and-low speed maglev train should provide a minimum thrust of 687.8 N

When changing the angle between the magnetization direction of two adjacent permanent magnets $\beta$, the number of the permanent magnets $n_p$ in a pair of poles can be obtained:

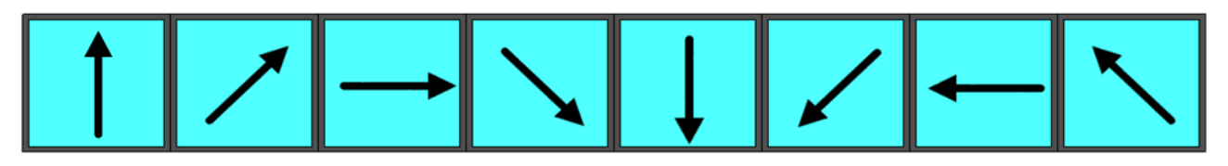
$$n_p = 360/\beta \qquad d_a = 2\tau / n_p$$

Due to the restrictions of the machining accuracy and the mechanical strength of the aluminum cabinet, we just analyze the three cases of $\beta$ = 36°, 45°, and 90°.

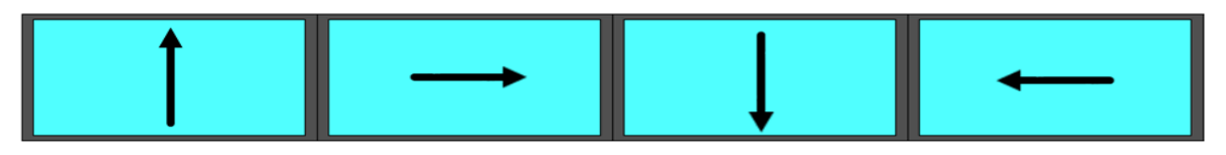
The phase current amplitude of the three finite element models is equal to 182.8 A.



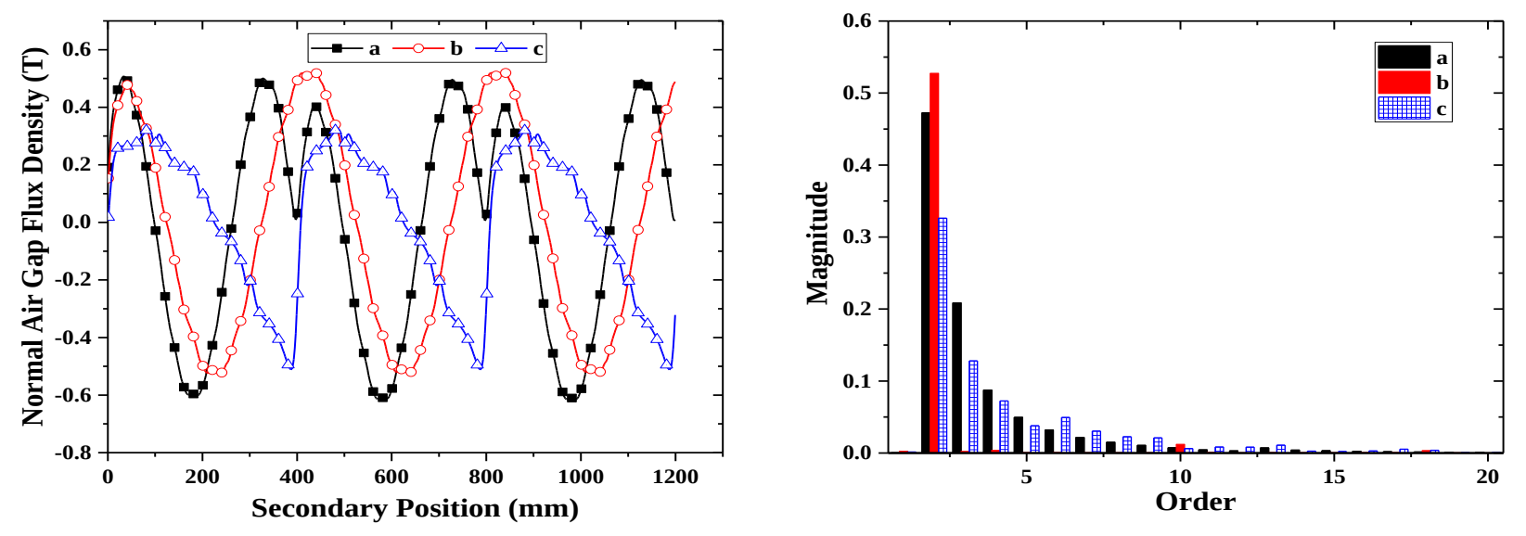
(a) $\beta$ = 36°



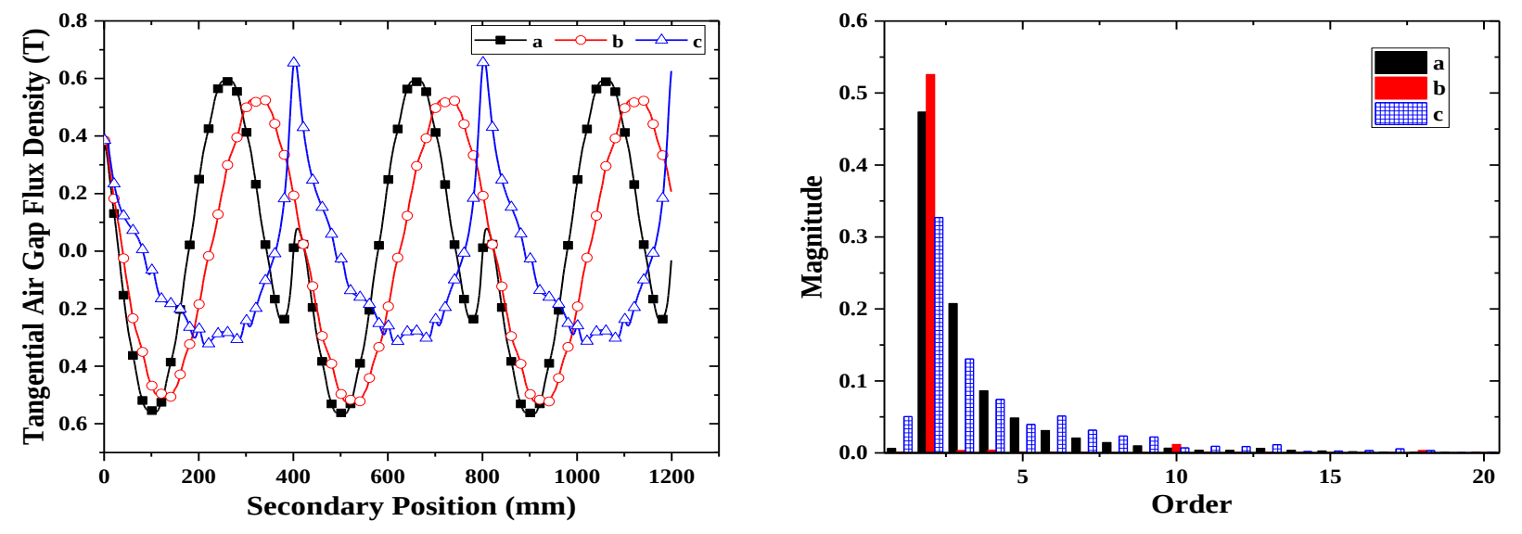
(b) $\beta$ = 45°



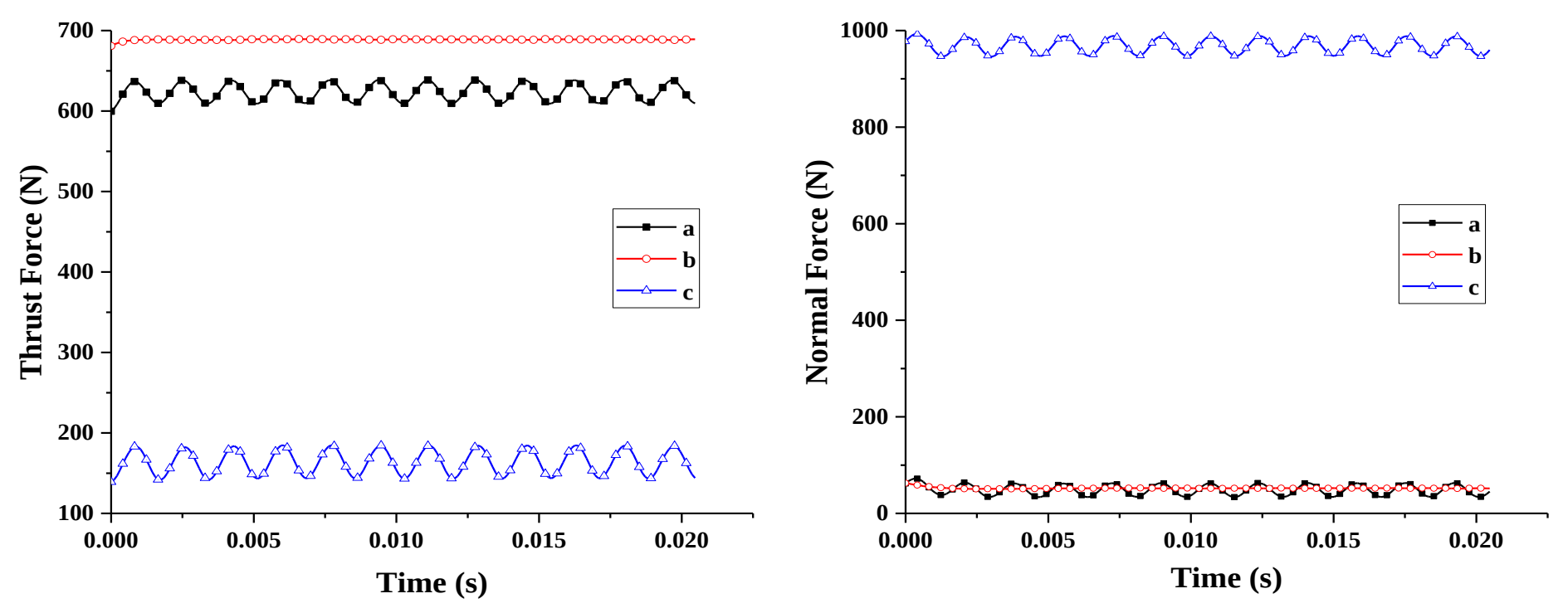
(c) $\beta$ = 90°



Normal air gap flux density waveforms and the harmonic spectra of the three cases



Tangential air gap flux density waveforms and the harmonic spectra of the three cases



The performance of case b is the best, at which the thrust force is 688.9 N with a ripple of 0.19%, the normal force is 52.0 N, the propulsion efficiency is 95.17%, and the power factor approximately equal 1.0.

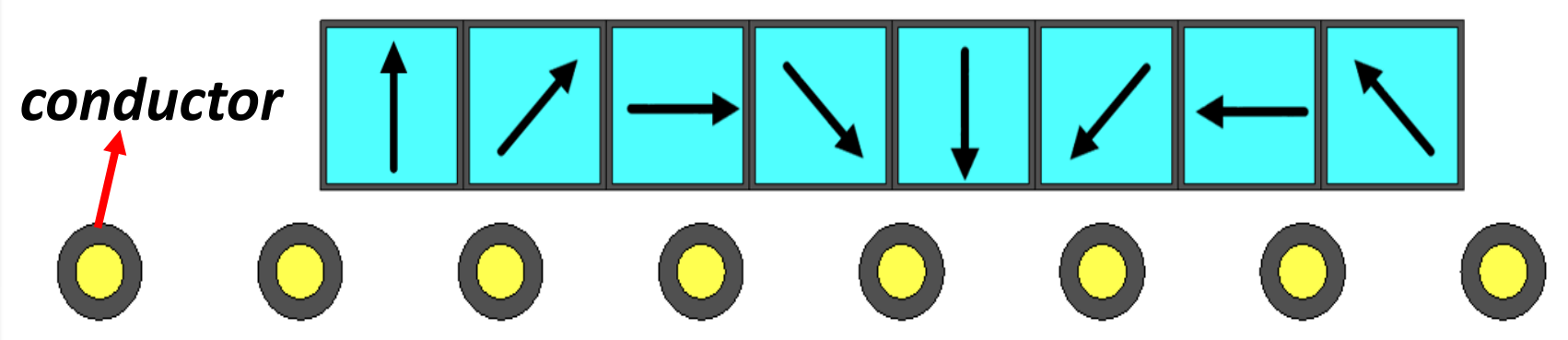
### Different cross-sectional shapes of the conductor

Keeping the insulation thickness of the winging, length of the air gap, and the cross sectional area of the conductor unchanged, five different cross-sectional shapes of the conductor will be analyzed.

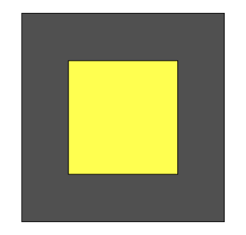
The conductor cross-sectional area is 201 mm$^2$. The ratios of length to width of rectangles (a), (b), and (c) are 1:1, 2:1, and 8:1.

The angle between the magnetization direction of two adjacent permanent magnets of the coreless Halbach permanent magnet linear synchronous motor is 45°.

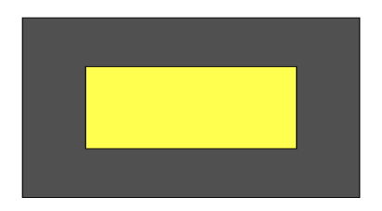
The phase current amplitude of the three finite element models is equal to 182.8 A.



(a)

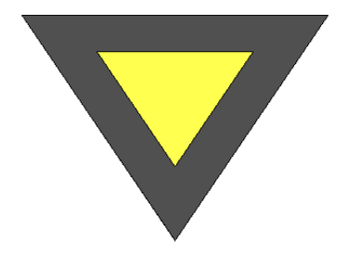


(b)



(c)

(d)



(e)

## Coreless Halbach PM-LSM

### Different cross-sectional shapes of the conductor

| | Thrust force (N) | Thrust force ripple (%) | Normal force (N) | Normal force ripple (%) |
|---|---|---|---|---|
| a | 688.9 | 0.19 | 52.0 | 2.25 |
| b | 698.8 | 0.15 | 44.6 | 2.31 |
| c | 719.9 | 0.20 | 45.6 | 2.44 |
| d | 738.9 | 0.11 | 43.1 | 1.60 |
| e | 708.4 | 0.12 | 45.4 | 1.90 |

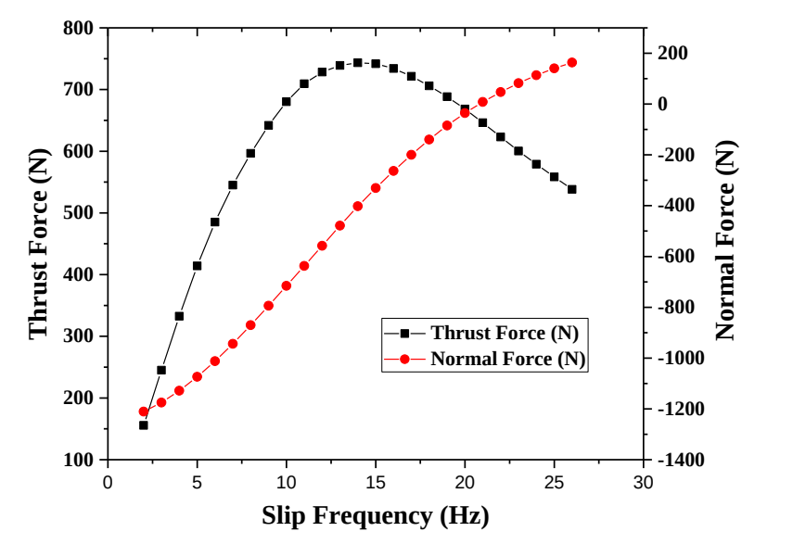
The case d is the best one. Its thrust force can reach up to 738.9 N, 7.2% higher than the permanent magnet linear synchronous motor with conductor of circular cross section and its normal force reduces to 43.1 N. Its propulsion efficiency is 95.78%, 0.61% higher than the permanent magnet linear synchronous motor with conductors of circular cross section.

## Linear induction motor

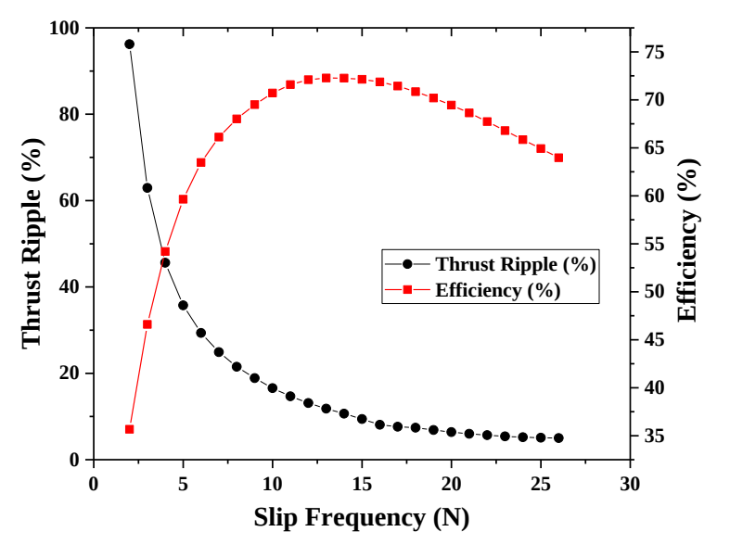
### Keeping the current constant

When the phase current amplitude of the finite element model of the linear induction motor is 174 A at different slip frequency, the reference slip frequency will be determined to be 19 Hz.

At the reference slip frequency, the thrust force of the linear induction motor is 688.2 N with a ripple of 6.83%, the normal force is -84.3 N, the efficiency is 70.18%, and the power factor is 0.814



Thrust force and normal force of the linear induction motor at different slip frequency



Thrust force ripple and efficiency of the linear induction motor at different slip frequency

### Keeping the thrust force constant

Because the thrust force ripple is relatively large at lower frequency, <19 Hz, we just analyze the efficiency of the linear induction motor when its slip frequency is higher than 19 Hz.

In order to obtain the required thrust force at slip frequency higher than 19 Hz, we must increase the input current. But a larger current will lead to lower efficiency, so we choose the optimal slip frequency as 19 Hz.

## Performance comparison

### Comparison of the two driving systems

| | LIM | PM-LSM | PM-LSM(S) |
|---|---|---|---|
| Efficiency | 70.18% | 95.17% | 95.78% |
| Power factor | 0.814 | 1.0 | 1.0 |
| Thrust force ripple | 6.83% | 0.19% | 0.11% |
| Normal force (N) | -84.3 | 52.0 | 43.1 |
| Mass of aluminum (t) | 163.9 | 223.0 | 223.0 |
| Mass of si-steel (t) | 16.4 | 0 | 0 |
| Mass of permanent magnets (t) | 0 | 12.22 | 12.22 |
| Total manufacturing cost of motors ($) | 3.9e+5 | 1.963e+6 | 1.963e+6 |
| Total cost of power utilization ($) | 1.878e+7 | 1.385e+7 | 1.376e+7 |
| Total cost of the driving systems ($) | 1.917e+7 | 1.581e+7 | 1.572e+7 |

The PM-LSM(S) represents the PM-LSM of rectangular conductor section with aspect ratio of 8:1.

Through the comparison of the two driving systems, we can see that the coreless Halbach permanent magnet linear synchronous motor is better for driving the mid-and-low speed maglev train.

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