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Characteristic Analysis of the Influence of Auxiliary Teeth and Notching on the Reduction of the Detent Force of a Permanent Magnet Linear Synchronous Machine

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Abstract

This study considered the reduction of the force ripple of a permanent magnet linear synchronous machine (PMLSM). The PMLSM has a relatively large magnetic air gap; thus, a slotted type of stator structure is generally employed. Furthermore, the detent force, which is caused by energy imbalances owing to the interaction between the tooth-slot structures and the permanent magnets (PMs), must be minimized for start-up operation. There-fore, in this study, the addition of auxiliary teeth and teeth notching are employed to reduce the detent force. In particular, the influence of the auxiliary teeth and notching on the detent force was analyzed, and an experiment was performed for verification.

Analysis Model Precondition for the Detent Force of the PMLSM

❖ Analysis Model

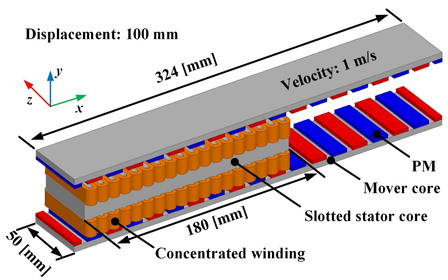

FIG. 1. Structure of PMLSM.

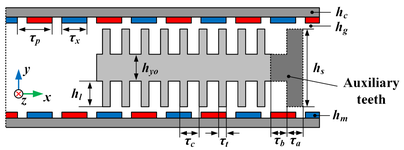

FIG. 2. 2D model of PMLSM and structure of auxiliary teeth.

TABLE I. Specifications of the PMLSM Model.

Parameter	Value	Parameter	Value
h_c	5 mm	h_m	3 mm
h_g	3 mm	h_s	40 mm
h_{yo}	14 mm	τ_p	18 mm
τ_x	13 mm	τ_a	0-18 mm
τ_b	0-18 mm	τ_c	10 mm
τ_t	4 mm	*Stack length*	50 mm
Mover length	324 mm	*Stator length*	180 mm
Velocity (max)	π m/s	*Displacement*	100 mm
Resistance	0.85 Ω	*Inductance*	1.35 mH
Pole number	18 poles	*Slot number*	18 slots
Turns per coil	20 turns	*Turns per phase*	12 coils
D	100 mm	*Speed of BLDC*	600 rpm

❖ Performance of the Design and the Manufactured Model

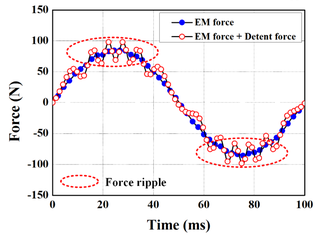

FIG. 3. Force analysis of slotted-type PMLSM.

- ✓ Fig. 3 shows the performance force at rated output power conditions.
- ✓ The value of the force in the generating mode is 100 N, but this result includes the detent force and the detent force value is 15 N.
- ✓ Thus, the maximum value of the electro-magnetic (EM) force is 85 N.
- ✓ Therefore, in order to limit the force ripple, the value of the detent force should not surpass a limit value of 5 N.

Analysis of Detent Force

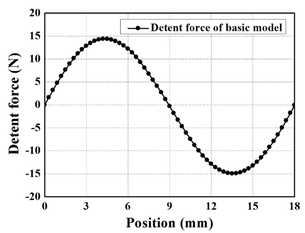

FIG. 4. Detent force analysis of the basic model.

➢ Detent force formula

$$F_d = \frac{dW_c}{dx} = \frac{L_z}{l_g \mu_0} \int_{S_0} B_y B_x ds, \quad W_c = \int \frac{B_s^2}{2\mu_0} dv$$

- ✓ Here, L_z, l_g, B_y, B_x, S_g, and μ_0 are the active mover length, air gap width, normal flux density in the air gap, tangential flux density in the air gap, air gap surface area, and permeability of air, respectively.
- ✓ The detent force result for the basic model is shown in Fig. 4.
- ✓ Given that its maximum value is 15 N, it should be reduced by a method that uses the auxiliary teeth and notches

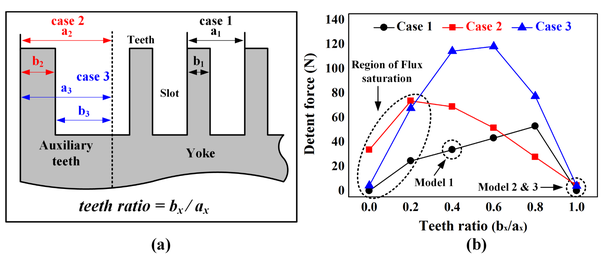

FIG. 5. Analysis model according to teeth ratio and analysis result.

Parametric Analysis of the Basic Slot Model and Auxiliary Teeth

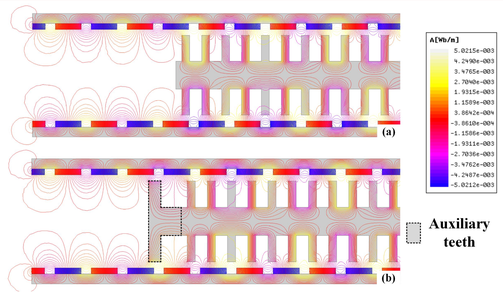

FIG. 6. Distribution of the flux line according to the auxiliary teeth.

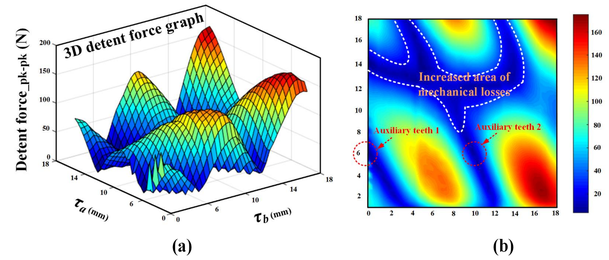

FIG. 7. Manufactured auxiliary teeth and parametric analysis results of the auxiliary teeth for detent force reduction.

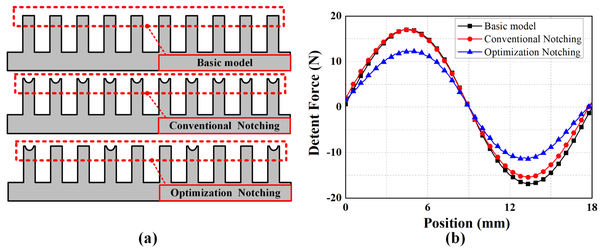

FIG. 8. Analysis of notching methods: (a) notching of teeth, (b) comparison of results of detent force.

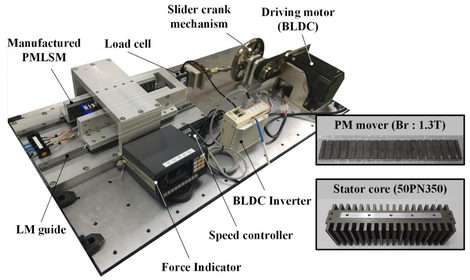

FIG. 9. Prototype PMLSM and experimental setup.

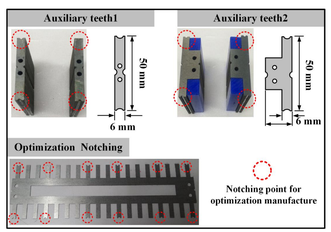

TABLE II. Optimum Auxiliary Teeth Specifications.

Subject	*Auxiliary teeth 1*	*Auxiliary teeth 2*
τ_a	6 mm	0 mm
τ_b	6 mm	10 mm
Detent force	4.8N	5.2N

FIG. 10. Optimized auxiliary teeth and stator notching.

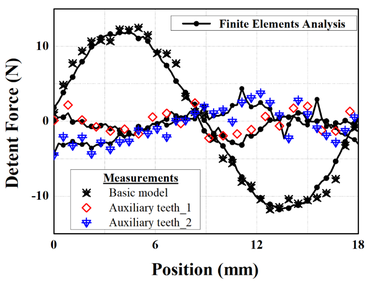

FIG. 11. Experimental results of the detent force with auxiliary teeth and notching of teeth.

Conclusion

- ✓ In this study, the detent force of a PMLSM was analyzed using FEA. In general, the detent force influenced the force ripple, especially from imbalanced magnetic energy in the air gap.
- ✓ The imbalanced magnetic energy is a result of the slotting effect of the stator structure. Therefore, the reduction of the detent force is important in the design of the machine. Two different models of auxiliary teeth and notching are used for parametric analysis.
- ✓ In addition, optimum point models are manufactured for experimental verification. The results reduce the detent force to 10% of the initial design model.

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