Reduction Design of End Edge Effect in Stationary Discontinuous Armature PMLSM combined with Skewed Magnets And Stair Shape Auxiliary Teeth

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Abstract – In recent years, a permanent magnet linear synchronous motor (PMLSM) hasbeen used in various kinds of transportation applications for its relative high power densityand efficiency. The general transportation system arranges the armature on the full length oftransportation lines. However, when this method is applied to long distance transportationsystem, it causes increase of material cost and manufacturing time. Thus, in order to resolvethisproblem, we suggested stationary discontinuous armature PMLSM. However, the stationary discontinuous armature PMLSM contains the edges which always exist asa resultof the discontinuous arrangement of the armature. These edges become a problem becausethe cogging force that they exert bad influences the controllability of the motor. Therefore, inthis paper we proposed the combination of skewed magnets and stair shape auxiliary teeth toreduce the force by edge effect. Moreover, we analyzed the influence of the design factors byusinga3-D finite element method (FEM) simulation tool.

Keywords: Linear motor, PMLSM, Stair shape auxiliary teeth, End edge cogging force, Finiteelement analysis

Introduction

Recently, current main driving source of Permanent Magnet Linear Synchronous Motors (PMLSMs) is the short-distance transportation system. However, the PMLSMhas been more widely used in the factory automation (FA)field such as transportation system than the existing systemwhich uses rotation machine, and has been also used invarious kinds of transportation applications for its relativehigh power density and efficiency [1]. According to thesesituations, the importance of the long-distance heavy loadtransportation system in PMLSM is also steadily increasing, and lotsofresearchresultsare shown [2-4]The general transportation system arranges the armatureon the full length of transportation lines. However, when this metho disapplied to longd istance transportation system, it causes increase of material cost and manufacturing time. Thus, in order to resolve this problem, we suggested stationary discontinuous Armature PMLSM (SDAPMLSM) which is able to decrease the number of winding sand amount of iron required. Shows schematic representation sof SDAPMLSM.However, as shown in Fig.1, when the armature is arranged discontinuously the edge always exists due to thestructure. For this reason, the end edge cogging force whichis generated between the entrance end (entry interval) andthe exit end (ejection interval) has become a problem. Dueto the effect of the force that generates at the edge, it hasbecome a problem that the velocity of the mover is differentfrom that commanded velocity when the mover moves fromfreewheelingtore-acceleration ordeceleration [5]. This hunting causes the vibrations and noise in the mover, and inthe worst case, step out due to load disturbance. Thus, in the SDAPMLSM, the reduction of cogging force at each edgeis highly desirable to ensure the smooth operation of themover between freewheeling regions. In order to reduce thecogging force, many studies are in progress such as skew ofpermanentmagnetandinstallation of auxiliary poleandteeth [6]. However, the studies that combine these methodsto minimize the cogging force are insufficient. Therefore, inthis paper, we installed stair shaped auxiliary teeth which istransformation of auxiliary teeth as the general reductionmethod of end edge cogging force. Moreover, we analyzedthe characteristics of changes in cogging force through 3-Dnumericalanalysisusingfiniteelementmethodanddesigned the auxiliary teeth of stair shape thatminimizestheendedge coggingforce.TheBasicModel ofSDAPMLSM

TheSpecificationsofSDAPMLSM

The full length of PMLSM's mover which is 264 mmwith the 30 degree skewed 8-pole permanent magnets ofNd-Fe-Btypewasarrangedonthemagneticplate.Thepermanent magnet itself had a length of 26 mm, width of 3mm, and pole pitch of 30 mm, while the armature had a fulllength of 360 mm. Winding method utilized in this studywas concentrated winding, and the number of turns per onephase was 75. There were 9 slots with slot pitch of 40 mm,and the air-gap between the armature and the mover was 5mm. The specifications of SDAPMLSM are shown in Table1.

Table1. Thespecificationofstationarydiscontinuousa rmaturePMLSM

	Parameter	Value(Unit)
Armature	Numberofslot	9(slots)
	Slotwidth(x-axis)	24(mm)
	Teeth width(x-axis)	16(mm)
	Teethheight(y-axis)	14(mm)
	Armaturelength	360(mm)
	Slotpitch	40(mm)
	Winding	Concentrated
	Turnsperonephase	75(turns)
Mover withPM	PMtype	Nd-Fe-B
	Residualmagneticflux density	1.25(T)
	Numberofpoles	8 (poles)
	Skewangle ofPM	30(deg)
	Magnetlength(x-axis)	26(mm)
	Magnetthickness(y-axis)	3(mm)
	Polepitch	30(mm)
	Backironheight	6(mm)
	Backiron length	264(mm)
Airgap		5(mm)
Stacklength		50(mm)

SkewedMagnets

PMLSM should be set as (1) so that the skew angle ofcogging force can cause a phase difference of 180 degree inorder toreducethecoggingforceefficiently[7].

$$\text{SkewAngle}=\frac{GCD}{2\tau_p}\times 180^\circ \quad (1)$$

GCD is the greatest common denominator of pole pitchand slot pitch. When the pole pitch is 30 mm and the slotpitch is 40 mm, skew angle is 30 degree. Therefore skewangle of permanent magnet is 30 degree. Fig. 2 shows amodelwithskewedmagnets.

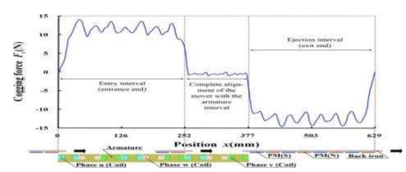


Fig.2. Shapeofskewedmagnets

AnalysisofBasicModelwithSkewedMagnets

Inordertoanalyzetheeffectofthecoggingforcegenerated from the end edge, we used the 3-D numericalanalysis using finite element method. The number of nodesis 4831, and the number of elements is 11451. The amountof movement per step is an interval of 1mm. The 3-Dnumerical analysis result of cogging force waveform of thebasic model is shown in Fig. 3. As indicated by Fig. 3, themaximum end edge cogging force generated from the entrytoejectionintervalswhenthemoverentersthearmatureis ±14.61 N, and the maximum cogging force generated whenthemoverandthearmatureareincompletealignment intervalis±0.3N.

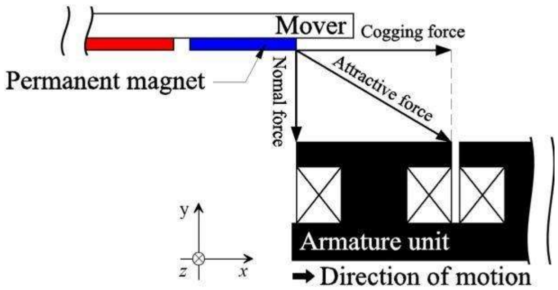


Fig.3. Coggingforceofbasicmodelwithskewedmagnets

EndEdgeCoggingForce

In discontinuous arrangement method of PML SM ,whena mover passes through the boundary between installationandnon-installations parts of the armature, anattractive force generated between the armature'score and the mover'spermanent magnetis greatly fluctuated.

Fig. 4 shows the effect that the force occurring at the endedge has on the mover. The attractive force generated whenthe mover enters the entry interval of the armature is anattractive force that directs toward the same direction as theoperationdirectionofthemover.
Thus, this force accelerates the mover by attracting ittoward the armature area. Furthermore, the attractive forcethat directs toward the opposite direction to the operationdirection of the mover is generatedwhen the mover exitsthe ejection interval of the armature. Thus it decelerates themoveras it functions as a returning force of themovertothe armature. Therefore, this end edge cogging force mustbereduced.

DesignParametersofStair ShapeAuxiliaryTeeth

The cogging force that generated when mover enters orexitsfromthearmatureis48.7timeslargerthancogging

force that generated when complete alignment of the moverwith the armature. Therefore, this large cogging force mustbe reduced. Stair shape auxiliary teeth were installed at theedge of the armature in order to reduce the cogging forcegeneratedattheedge.AsshowninFig.5,designparam eters for the optimum design of the auxiliary teeth arerepresentedbytheintervaldistance(X)betweenthearm atureandtheauxiliaryteeth,thewidth(D)oftheauxiliarytee th,theheight(Y)of theauxiliary teeth,interval(Z) between steps, and number of stair steps (S), that wasfixed to 3 steps. Also, the laminated width was made equalto that ofthe armature.

1. **Design of the Stair Shape Auxiliary Teeth for Reduction of the End Edge Cogging Force**

CoggingForceaccordingtoeachStairShape

In the table 2, model No. 1-4 shows the maximum endedge cogging force relative to the adjustments to the heightof the auxiliary teeth (Y- height). In order to determine the heigh to fth eauxiliary teeth, the interval distance(X)between the armature and the auxiliary teeth was fixed at 1mm, which isminimum interval of the slot opening. Andthe width (D) of the auxiliary teeth was fixed at 19 mm, which was mostsuitable widthin the auxiliary teeth. Analysis tha the height of Y, theheightoftheteethincluding the cap of the armature, was decreased from 20mm to 2 mm interval was performed. As a result, 13.75 Nwas generated in cases No. 2 with the 18 mm height of stairshapearmature'steeth.Fig.6Showscomparedthemax imumendedgecoggingforceofmodelNo.1-4Cogging force increases and decrease based on the modelNo.2.Also,theyshowedthechangeintheendedgeco gging force of 0.8 N. Therefore, it was shown that it isdesirable to make theheight of thestair shape auxiliaryteethis smallerthanthatheightofthearmature'steeth.

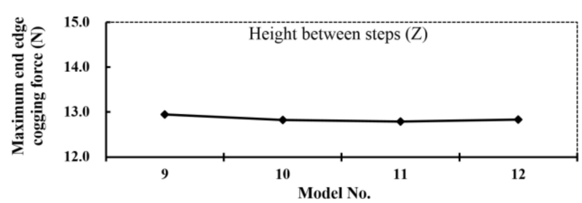
Then, in order to deduce the width (D) of the stair shapeauxiliaryteeth,theintervaldistance(X)betweenthear matureandtheauxiliaryteethwasfixedat1mm,whichis minimum interval of the slot opening. In the table 2,model No. 5-8 shows the maximum end edge cogging forceaccording to the adjustments to the width of the stair shapeauxiliary teeth. From Table 2, the width (D) of the stairshape auxiliary teeth was changed from 17 mm to 21 mmwith 1 mm intervals. As a result, 12.84 N was generated incases No. 6 with the 18 mm width of stair shape armature'steeth.Fig.7Showscomparedthemaximumende dgecogging force of model No. 5-8. Cogging force increasesand decrease based on the model No. 2. And they showedthechangeintheendedgecoggingforceof1.26N.Th erefore, adjustment to the width (D) of the stair shapeauxiliary teethisdesirableformorereducethecoggingforcethan theheight (Y). Based on the results of model No. 1-8, Y was fixed to 18mm and D was fixed to 18 mm in order to deciding Z andthe remaining parameter was selected as same as the above .The model adjusted Z was modelNo.9-12anditwaschanged from 2 mm to 6 mm with 1 mm intervals. Amongthe 4 models adjusted Z, the end edge cogging force ofmodelNo.11wasgenerated12.79N.Fig.8Showscompare d the maximum end edge cogging force of modelNo. 9-12. In adjusted Z, the change in end edge coggingforcewas 0.16 N less than in adjusted Y, D. However,maximum end edge cogging force was more reduced thanprevious models. Thus, 5 mm was found to be the mostappropriateheight for Z.

Finally, the interval distance (X) between the armatureand the stair shape auxiliary teeth was deduced using 18mm, 18 mm and 5 mm as the height, width and intervalbetween steps of the stair shape auxiliary teeth. The modeladjusted interval distance (X) was model No. 13-16 and itwas changed from 1 mm to 5 mm with 1 mm intervals. Fig.9 Shows compared the maximum end edge cogging force ofmodelNo.13-16.Cogging forceincreasesanddecreasebased on the model No. 2. And they showed the change inthe end edge cogging force of 1.05 N. But the force wasincreasedat2-5mm. Therefore, the appropriate pitch of Xis1mm.

Table2. Maximumendedgecoggingforceofeachmodel

		X mm	Y mm	D mm	Z mm	Maximum end edgecogging force
Model No.	1	1	20	19	3	14.54(N)
	2	1	18	19	3	13.75(N)
	3	1	16	19	3	13.83(N)
	4	1	14	19	3	14.47(N)
	5	1	18	17	3	13.17(N)
	6	1	18	18	3	12.84(N)
	7	1	18	20	3	13.30(N)
	8	1	18	21	3	14.10(N)
	9	1	18	18	2	12.95(N)
	10	1	18	18	4	12.82(N)
	11	1	18	18	5	12.79(N)
	12	1	18	18	6	12.83(N)
	13	2	18	18	5	13.39(N)
	14	3	18	18	5	12.85(N)
	15	4	18	18	5	13.90(N)
	16	5	18	18	5	13.84(N)

As a result, the model of optimized auxiliary teeth wasmodel No. 11 and its appropriate pitch of X was 1 mm,height of Y 18 mm, the width of D per 1step of stair shapedauxiliaryteethwas18mm, the interval betweenthe steps of Z was 5 mm, and the numbers of stair-steps S was 3 steps.Fig. 10 shows the basic model and the waveform of endedge cogging force of the optimized stair shaped auxiliaryteeth.



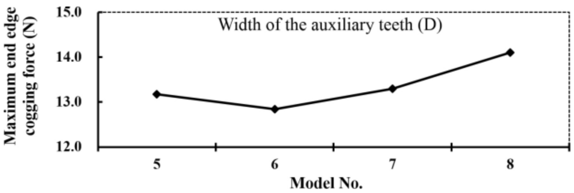


Fig.7. Maximumendedgecoggingforceaccordingtothea djustmenttothe D-length

Fig.8. Maximumendedgecoggingforceaccordingtothea djustmenttotheZ-height

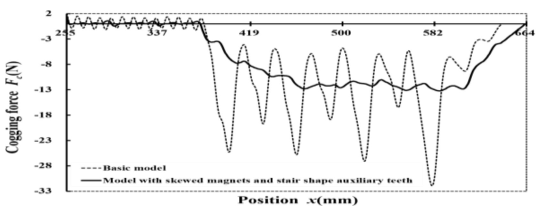
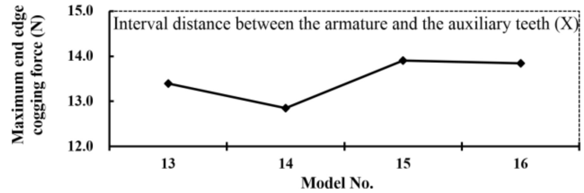


Fig.10. Endedge coggingforcewaveformsofeachmodel

Conclusion

In this paper, we proposed the stair shaped auxiliary teethinstallation method in order to reduce the end edge coggingforcewhichfunctionsasthethrustforcerippleatt hestationarydiscontinuousarmaturePMLSM.First,wea nalyzed the end edge cogging force of the basic modelthrough the 3-D numerical analysis. Maximum end edgecoggingforceofbasicmodelwas31.94N.Next,wei nstalledskewedmagnetsandweselectedthedesignedpar ameter for the optimum design of the installed auxiliaryteeth of stair shape then examined the end edge coggingforce.Asaresult,theappropriatepitchofXfromt hearmature in the case of the optimized stair shape auxiliaryteeth was 1 mm, height of Y 18 mm, the width of D per1step of stair shaped auxiliary teeth was 18mm, the intervalbetween the steps of Z was 5 mm, and the numbers of stair-stepsSwasfixedto3steps.Themaximumendedgecoggin g force of optimum designed model was 12.79 N. Itwas decreased 60.00 % in comparison to the basic modeland12.46% of reductioncomparedtothebasicmodelusingskewedmagnet s.Thus,theeffectivenessoftheproposed model with auxiliary teeth of stair shape in



regardthereductionoftheendedgecoggingforcehasbeenve rified. Also, parameter which was the most affected toreduce the end edge cogging force is the width (D) of theauxiliary teeth that showed change in 1.26 N. It must beconsideredintheoptimaldesignwhichcitedourpaperbec ause it is the most sensitive part of the optimal shapedesign.

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