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The Optimal Design of Single Sided PMLSM for Considering Winding Temperature Rising according to Thickness of Teeth

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Abstract – This research deals with design of the maximum thrust density with considering winding temperature rise of single-sided PMLSM. The temperature rise of winding which caused to machine characteristics such as copper loss, iron loss and efficiency was analyzed by FEM. The maximum allowable current density was calculated within the allowable temperature. The effects of loss and efficiency according to temperature characteristic were confirmed.

Keywords: PMLSM, Winding temperature, Thrust, Thermal analysis

1. Introduction

The PMLSM has high thrust density, high speed and low maintenance costs. So it has been widely used in industries such as manufacturing equipment of semiconductors and PDP/LCD [1]. The productivity of these devices depends on the acceleration and deceleration characteristics of PMLSM. In order to increase productivity, the winding temperature which is much closer to the allowable temperature is severely operated [2]. Therefore, the winding temperature must be considered from the magnetic circuit design process [3]. Also the maximizing design of thrust density is needed to improve productivity in design stage [4, 5]. The ways of maximized thrust density are using a material of high permeability in core, high remanent flux density of PM and minimization air-gap, maximizing magneto-motive force [6]. However to maximize the thrust density through material of core or permanent magnet is very inefficiently method in expense. Also method of reducing mechanical air-gap has physical limitation. Thus, the most efficient method to maximize the thrust density is magneto-motive force maximization design which is proportional to multiplication of coil turn and current density. However, in conventional design methods, the current density is determined by the designer's experience and the thickness of winding is selected to design parameter, but the temperature rise was not considered. So continues redesign is necessary to meet the performance requirements. Thus, a magnetic field of PMLSM was analyzed with thermal analysis to minimize trial error in this paper. The maximum allowable current density was calculated within the allowable temperature according to changing height of the winding. The effects of changing temperature on the machine performance were analyzed.

2. Thermal Analysis of Single-sided PMLSM

2.1 Temperature rise test

Fig. 1 shows the structure of basic model and Table 1 shows the specifications of basic model by the temperature rise test. The permanent magnet, epoxy and coil which are among the constituting material of single-sided PMLSM have to be considered by temperature.

The permanent magnet is not easily demagnetized at 140(°C) high temperature and the coil or epoxy which are the H-grade of allowable temperature 180(°C) can be easily obtained. The demagnetization of permanent magnet according to temperature rise is the most concerned component in rotary machine. However, the epoxy is the most concerned component in PMLSM. Because the mechanical air gap is generally very small in PMLSM. So damage and crack are produced in over 140(°C) temperature. Therefore, the dust which makes critical problem in clean room is produced by reaching permanent magnet and epoxy. So it makes damage and burn of mover. Accordingly, the allowable coil temperature of single-sided coreless PMLSM was decided as 105(°C) with safety which the inside temperature of equipment is supposed as maximum 25(°C) and the limit of temperature rise is determined as 80(°C) in this paper. If the allowable temperature of coil is exceeded by temperature rise, the primary object of performance of wouldn not be implemented. So the temperature rise test must be conducted after designing and manufacturing.

The temperature rise test which determined the rating of machine was tested on the condition of duty type S5 (Periodic control including electrical brake) at a Fig. 2 [7]. The test motor was installed on a test jig and the operating conditions were set up as following. An acceleration was 20(m/s^2), a maximum velocity was 2(m/sec), a moving distance was 600(mm), and the additional weight was

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installed in a mover to supply sufficient load at the acceleration. The temperature sensor was inserted in the mover. The results of this test are as following. Continuous thrust was 657(N) at natural cooling, continuous current density was 6.48(A/mm^2) and internal temperature of winding was 96.6(°C) at that time.

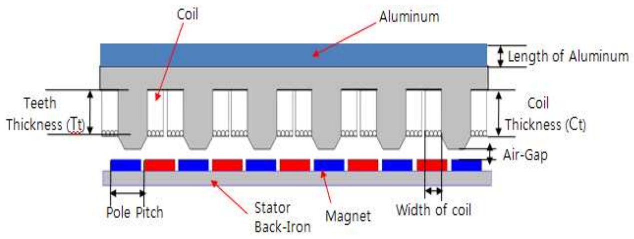
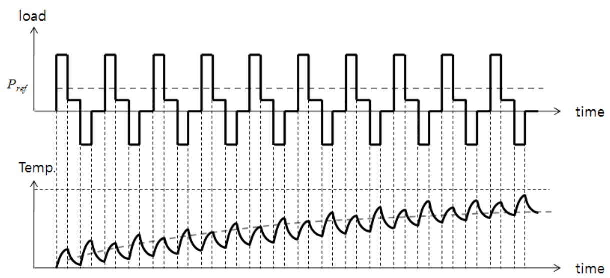


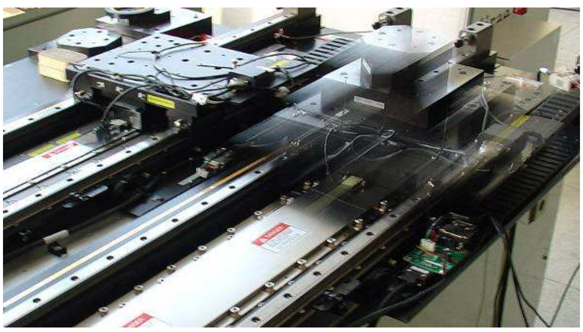
Fig. 1. Structure of basic model

Table 1. Specifications of basic model

Item	Symbol	Value	Unit
Pole Pitch	-	30	mm
Thickness of Teeth	Tt	16.80	mm
Thickness of Coil	Ct	16.85	mm
Width of Coil	-	13	mm
Number of Coil	-	608	Turn/2ea
Air-gap	-	1.4	mm
Continuous Current Density	-	6.4955	A/mm^2
Continuous Force	-	657	N
Allowable Coil Temperature	T	105	°C



(a) Test pattern (S5)



(b) Experiment equipment

Fig. 2. Temperature rise test

2.2 Thermal analysis

A heat transfer mechanism is classified into a conduction, convection and radiation. The heat transfer by radiation is generally neglected in the motor. In case of conduction, thermal analysis can be easily analyzed since the thermal conductivity coefficients of every material are already specified. Table 2 shows heat conduction coefficient [8].

Table 2. Heat conduction coefficient

Materials	Thermal conduction rate	Unit
Copper	401	W/m· K
Air	0.026	
Epoxy	0.5	
Permanent Magnet(PM)	9	
Back-iron steel	51.9	
Aluminum	237.5	

However, convection coefficients are very difficult to determinate accurately. The ‘convection heat transfer coefficient’ is not a property of materials; this value is determined by the surface shape and the flow property which generates convection heat transfer [9]. Thus, the selected design parameter which is winding height does not change convection surface shape and flow property. It means convection heat transfer coefficient is not altered. The convection heat transfer coefficient is inversely calculated by the experiment result of basic model. This was deducted from experiment and applied to thermal analysis. Fig. 3 shows temperature distribution that convection heat transfer was applied by thermal analysis.

In comparison with internal temperature at 96.4(°C) of coil by thermal analysis and internal temperature at 96.6(°C) of coil by experiment, convection heat transfer coefficient was properly selected. Also, the spare coil temperature was about 8(°C) that was compared to allowable temperature at 105(°C) of coil. Thus, the maximum allowable current density was recalculated within the allowable temperature. Table 3 shows the maximum thrust in this model.

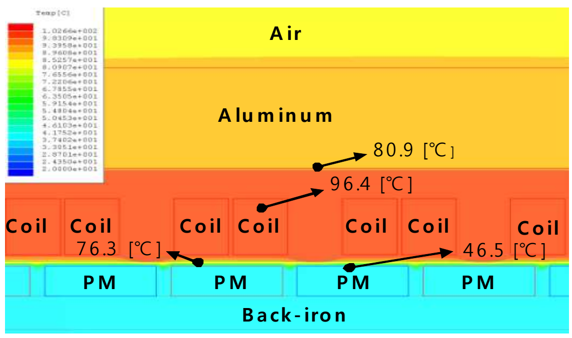


Fig. 3. Temperature distribution of basic model by thermal analysis

Table 3. Recalculation the maximum allowable current density of basic model

Input Current (A)	Current Density (A/mm^2)	Winding Temperature (°C)	Thrust (N)
6.53	6.4955	96.40	668.35
6.85	6.8138	104.88	709.12

2.3 Maximum current density calculation and thrust according to height of the core

In conventional design method to maximize the thrust density, it was a general method that increases winding turns to grow magnetic force when the experiment value of the current density was fixed. The height of the core has to be increased as much as winding turn is increased. In case of increasing core height and same current density as conventional design methods, it is expected that the rising of trust density as much as the increase of trust coefficient. When the height of core is getting higher, the cooling effect becomes worse. So the temperature of the copper will be rapidly increased. Therefore, the thrust is not increased as much as the increments of the winding turn because copper loss is increased by internal resistance of the winding. The errors occurs with the first target of the device performance. So the design process of trial and error are repeated. Thus, the maximum allowable current density was recalculated by thermal analysis from design stage under the allow temperature of winding according to winding height in this paper. Fig. 4 shows that the process of the current density recalculation by thermal analysis.

Firstly, to confirm the changing of the core height, 9 models which is according to height of core were designed based on basic model. Table 4 shows that temperature margin of each model was figured out by thermal analysis after assumed current density by the experience value.

The thrust which fixed the current density did not consider the temperature characteristic so the error will be generated with real generating thrust at this time. Fig. 2 shows the temperature distribution chart of PMLSM according to the changing of the core height. When the winding turns were 176 (the height of core is 9.75mm), the highest temperature was calculated at 68.2(°C) in the winding because the good heat releases characteristic and the thrust can be increased by increment of the current density. However, when the winding turn was 592 (the height of core is 32.73mm), the machine was damaged because the highest temperature, which was 202.7(°C), exceeded in allowable temperature. That is, in case of thinner model of core height, the heat emission characteristic was improved so the spare temperature existed. However, in case of higher model of core height to increase thrust density, the heat emission characteristic became worse so coil temperature exceeded the allowable temperature. The maximum current density which did not exceed the allowable temperature was calculated according to height of core, which was shown in Table 5.

In case of the thinner model of the core height, the current density can be designed as the temperature margin. On the other hand, in case of the thicker model of the core height, the current density has to be dropped not to exceed the allowable temperature.

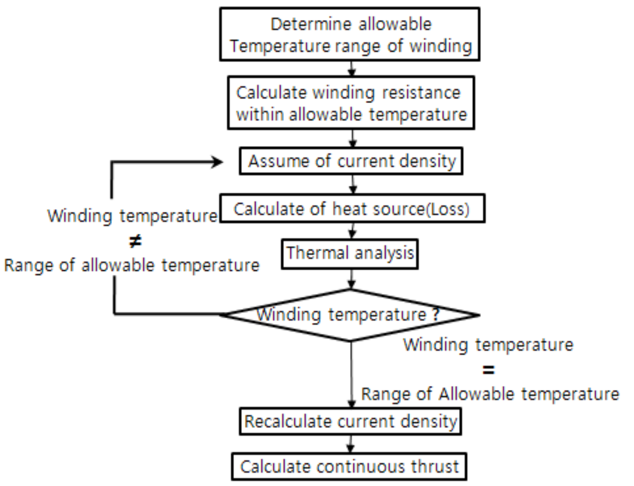
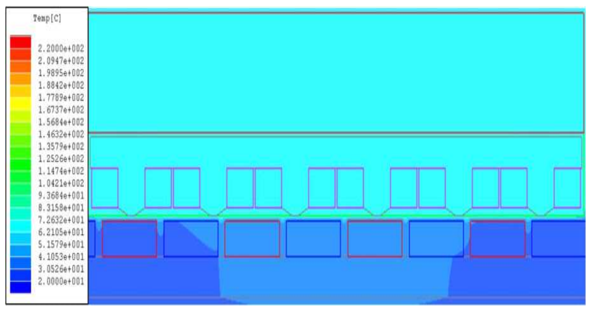


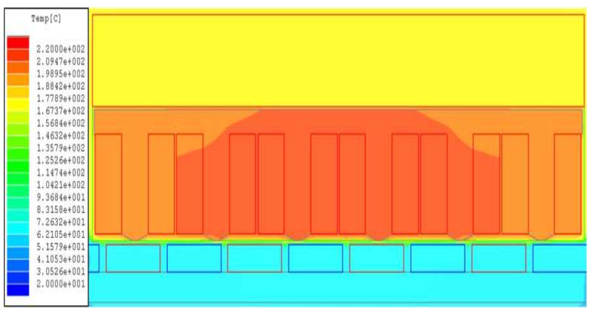
Fig. 4. The process of the current density recalculation

Table 4. Spare temperature and thrust according to height of winding

Height of core(mm)	Temperature (°C)	Spare temperature (°C)	Thrust (N)
9.75	68.2	36.8	425.7
11.51	76.9	28.1	495.6
13.32	85.9	19.1	565.6
15.04	95.2	9.8	639.7
16.80	104.8	0.2	709.1
18.56	114.7	-9.7	768.1
20.33	124.9	-19.9	836.1
25.62	156.8	-51.8	1030.3
32.68	202.6	-97.6	1281.6



(a) Height of the core : 9.75(mm)



(a) Height of the core : 32.73(mm)

Fig. 5. Distribution temperature chart according to height of the core

Table 5. Recalculation of current density

Height of core (mm)	Current density (A/mm^2)	Current (A)	Temperature (°C)	Thrust (N)
9.75	8.83	8.88	104.8	549.7
11.51	8.15	8.20	104.9	591.6
13.32	7.61	7.66	104.9	632.1
15.04	7.17	7.21	104.7	673.4
16.80	6.81	6.85	104.8	703.3
18.56	6.50	6.54	105.0	733.7
20.33	6.22	6.26	104.7	764.9
25.62	5.60	5.63	104.9	850.9
32.68	5.02	5.5	104.8	950.1

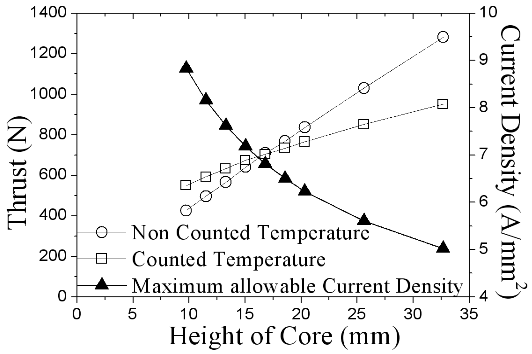


Fig. 6. Maximum allowable current density and thrust

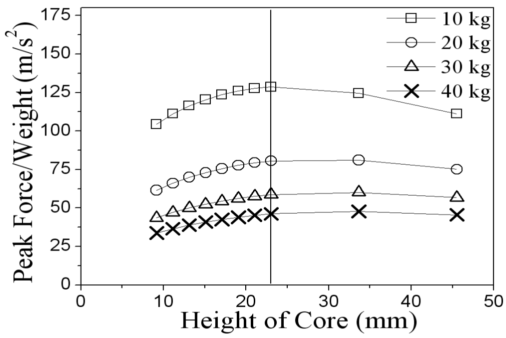
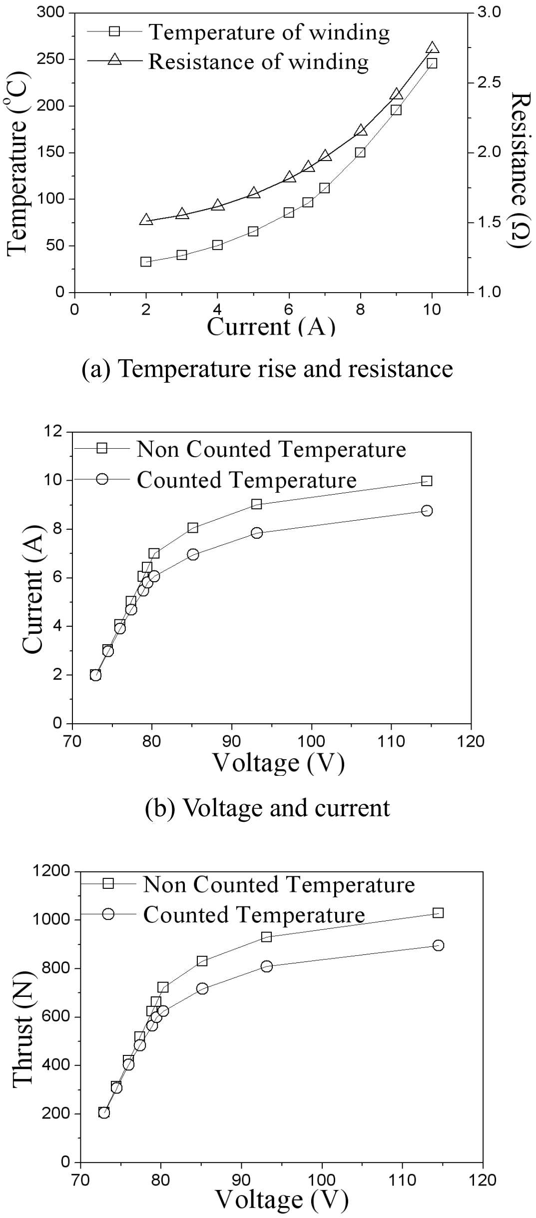


Fig. 7. The maximum allowable current density and thrust

Fig. 6 represents the comparison with thrust which was without consideration of temperature rise when the current was fixed and thrust which was with consideration of coil temperature when the allowable current flowed. As expected earlier, generating thrust which was without consideration of temperature rise when the current density was fixed had an error with real generating thrust. In case of considering the temperature characteristic in the winding as shown in Fig. 3, when the height of the core is 9.75(mm), the current density was increased from 6.5(A/m^2) to 8.57(A/m^2), and the thrust was also increased from 475.71(N) to 549.734(N). However, in case the height of the core was 32.73(mm), the current density was decreased from 6.5(A/m^2) to 4.92(A/m^2). So the thrust was decreased as 331.5(N) than without consideration of temperature rise. In other words to compare with design of fixed current density, in case of the thinner model of core height, the spare temperature are existed. So the thrust density can be increased. On the contrary, in case of the thicker model of core height, the real thrust density was decreased by temperature characteristic. Thus, the trial error will be minimized in the process of the design for considering temperature characteristic when the magnetic circuit is designed with the consideration of thermal analysis. In addition, the aspect of maximum thrust per unit weight was studied. In general, the PMLSM momentarily use the maximum thrust in acceleration-deacceleration state within 3 seconds. If the core height is higher, the maximum thrust cannot be obtained due to saturation of core in single-sided PMLSM. In general, the maximum current allows up to 300(%) of continuous current in momentary acceleration and deacceleration condition. However, maximum thrust dose not generate 300(%) by a saturation according to core height increasing. Therefore, the review of the maximum thrust is also required at the optimal design stage in single-sided PMLSM. Fig. 7 shows that the change of peak force(momentary generating thrust) per unit weight according to the height of the core. If the core height is getting higher, the maximum thrust would not be increased by the saturation. If the load is 10kg, the height core which is 23.03(mm) is optimal model to maximize acceleration of 128.6(m/s^2).

3. Loss Evaluation from Temperature Rise

The resistance was increased by rising temperature of winding. So the additional voltage drop was produced. Therefore, the voltage should be increased to get same thrust. Fig. 8(a) shows changing temperature and resistance according to changing current of applying PMLSM in this paper. The temperature and the resistance were rapidly increased when the current which was over the allowable temperature was flowed. To generate same thrust, high voltage should be supplied than in case of without consideration of temperature rise by increased resistance according to temperature rise as a Fig. 8(b) and (c). To find the effect of the temperature rise, the voltage which is for flowing rating current of the basic model, the loss and efficiency were analyzed as table 6. In case of supplying 79.42(V) without consideration of temperature rise and the internal resistance of the coil is 1.468(Ω), the current will be 6.42(A) in coil. However, in case of considering temperature rise, the internal resistance of the coil was rapidly increased as 1.893(Ω). To flow the same current in the coil, the higher voltage should be inputted as 82.95(V) than without consideration of temperature rise. That is to say, the loss will be effected. The total loss was 274(W) by temperature rise and the efficiency was decreased by additional loss from 86.6(%) to 82.9(%).



(a) Temperature rise and resistance

(b) Voltage and current

(c) Changing of thrust

Fig. 8. The effect of machine characteristic according to temperature

Table 6. Loss and efficiency by temperature characteristic of basic model

	Without consideration of temperature rise	Consideration of temperature rise
Voltage (V)	79.420	82.950
Resistance (Ω)	1.468	1.893
Current (A)	6.420	6.460
Thrust (N)	662.007	666.936
Input (W)	1529.629	1608.318
Output (W)	1324.014	1333.872
Loss (W)	205.615	274.445
Efficiency (%)	86.550	82.930

4. Conclusion

The characteristic of temperature rise and the maximum allowable current density were calculated according to changing core height by thermal analysis in this paper. In case of thinner model of core height, the heat emission characteristic was improved and the spare temperature existed. So, the higher current density could be calculated, the thrust could be increased. On the other hand, in case of thicker model of core height for increasing thrust density, the heat emission characteristic became worse and the temperature of motor exceeded the allowable temperature. So, the error of theoretical thrust and real thrust was generated by estimating low current density in consideration of temperature characteristic. If the effect of changing temperature characteristic is considered using the thermal analysis in the design stage, trial and error of conventional method will be decreased. In case the higher voltage was supplied by changing resistance according to temperature rise, the same thrust would be generated. Additional loss and efficiency of basic model were calculated from the changing temperature.

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References

[1] Karita, Mitsuji, “Present Status of Linear Drives for Industry Applications in japan,” Proc. of LDIA01, pp. 462-467, October 2001.

[2] M. Sanada, S. Morimoto, Y. Takeda, 1997. “Interior Permanent Magnet Linear Synchronous Motor for High Performance Drives”, IEEE Trans. on Industry Application, Vol. 33, No. 4, pp. 966-972.

[3] S.R. Aid, W.N.L. Mahadi, K.M.Nor “Thermal Analysis of a Tubular Permanent Magnet Linear Generator using Multiphysics Solver” Proc. IEEE Region 10 TENCON 2005 Conf., CD-ROM, 6pp.

[4] Gieras j.F, Godkin, Mikhaill, “Status of Permanent Magnet Linear Motors in the United States,” Proc. of LDIA01, pp. 456-461, October 2001.

[5] K. Yoshida, J. Lee, Y. J. Kim, 1997. “3-D FEM Field Analysis in Controlled PMLSM for Maglev Vehicle”, IEEE Trans. on Magnetics, Vol. 33, No. 2, pp. 2207-2210.

[6] D. Ebihara, H. J. Kim, Y. Kawamotor, S. Torii, M. Watada, 1993, "Study of the Transport System with PM Type LSM", Annual Conference of IEEE Industry Applications Society, pp. 53-56.
[7] International Standard "IEC 60034-1 : 2008", Rotating Electrical Machines, Rating and Performance.
[8] Marignetti, Fabrizio, Delli Colli, Vincenzo "Thermal Analysis of an Axial Flux Permanent-Magnet Synchronous Machine", IEEE Trans. On Magnetics, Vol. 45, issue 7, pp. 2970-2975, July 2009
[9] P. Mellor, D. Roberts, D. Turner "Lumped parameter thermal model for electrical machines of TEFC design", Proc. Inst. Elect.

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