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The Improved Design of Double Sided Coreless PMLSM with Consideration of Rising Winding Temperature

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Abstract – This work deals with the optimal design of a coreless PMLSM (Permanent Magnet Linear Synchronous Motor) with consideration of rising winding temperature. The temperature distribution caused by copper loss in the coreless PMLSM was analyzed using a FEM (Finite Element Method). The thrust and current density where the winding temperature reaches the allowable temperature were calculated. The optimal model provides maximum thrust per unit weight.

Keywords: PMLSM, Thermal transfer, Thrust, Winding temperature

1. Introduction

The coreless PMLSM does not generate detent force and normal force. Consequently, it neither normal force nor velocity ripple. Because of the resultant fast response time, it has accordingly been widely used in superhigh speed precise industries such as in the manufacture of equipment for producing semiconductor wafers [1]. The productivity of these devices depends on the acceleration and deceleration characteristics of the coreless PMLSM [2].

In a coreless PMLSM, the effective thrust to load increases when the mover is lighter, because load is installed directly on the mover [3]. In other words, it can accelerate faster and it can increase productivity when the mover is lighter if two machines produce the same thrust.

The number of turns and the current density must be increased in order to produce greater thrust, because only winding exists in the mover [4]. However, the weight of mover rises if the number of turns is increased, and the winding temperature will rise if the current density is increased [5]. Consequently, the optimum points must be set.

It seems very simple to derive the optimal model which has maximum thrust per unit weight, if all design parameters are the same except for the winding height and current density [6]. The optimal model could be derived by carrying out a finite element analysis with variation of the number of turns assuming a current density value based on experience.

However, the thermal characteristics would be changed when the number of turns and the thickness of the mover change [7]. This means that the current density changes if the number of turns is changed. Accordingly, it would be complicated to derive an optimal model that takes winding temperature into consideration.

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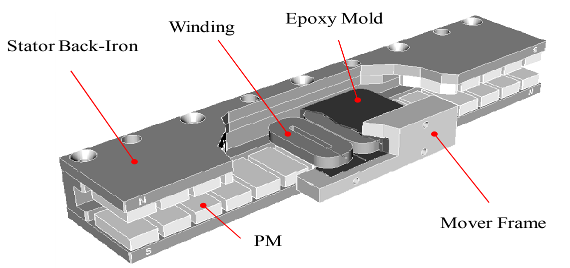
Therefore, the optimal design method of a coreless PMLSM considering coil temperature through a thermal analysis is suggested in this paper. Namely, the optimal model that produces the maximum thrust per unit weight is derived through calculation of the thrust by the computed current density when the winding temperature reaches allowable temperature. The validity of this approach is proven through a comparison of the results of calculations with the results of experiments.

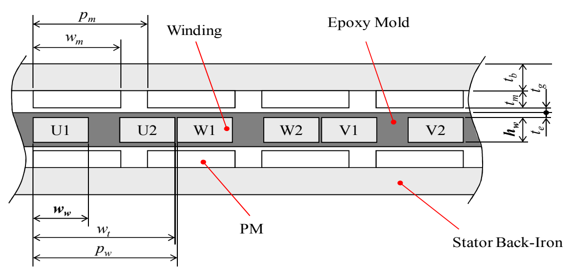
2. Basic Model

2.1 The structure and important dimensions

Fig. 1 shows the important dimensions and structure of the double sided coreless PMLSM considered in this paper.



(a) Structure



(b) Important dimensions

Fig. 1. The caption for a figure must follow the figure

Many design variables are presented in Fig. 1(b), but only winding turns and current density were selected as design parameters. With increasing number of turns, the winding height (h_w) and the thickness of the mover become higher.

2.2 Specification

Table 1 presents the principal specifications of the coreless PMLSM. The continuous load test, which determined the rating of the machine, was carried out by S5 (Periodic control including electrical break), as shown in Fig. 2 [8]. The test motor was installed on a test jig, and the operating conditions were established as follows: acceleration 25(m/s^2), maximum velocity 2.5(m/s), moving distances 150(mm), and moving mass including the mover 16(kg). A temperature sensor is inserted into the mover to measure the coil temperature. The continuous operation was controlled so as to saturate the increase of winding temperature at 80(°C) by the waiting time while the winding temperature was recorded at this condition.

From the results of the experiment, the continuous thrust was 227(N) at natural cooling and the continuous current density was measured as 8.48(A/mm2).

Table 1. Principal Specifications

Item	Symbol	Value	Unit
Thickness of PM	t_m	7.5	mm
Length of PM	l_m	52.0	mm
Height of Winding	h_w	9.4	mm
Continuous Current Density	J_c	8.48	A/mm^2
Continuous Thrust	F_c	227	N
Limit of Temp. rise	ΔT	80	C

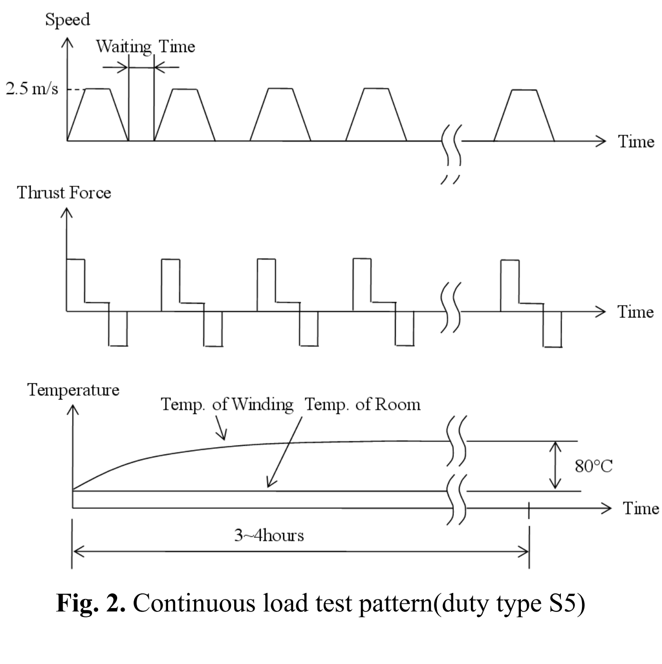
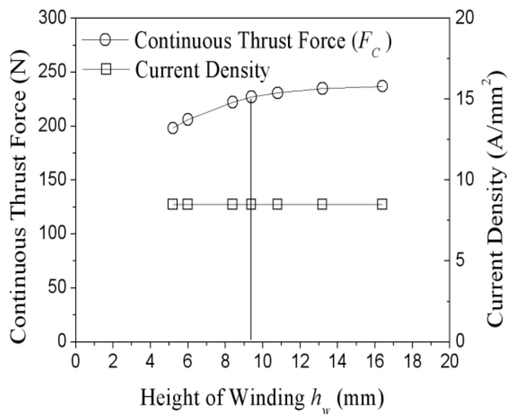
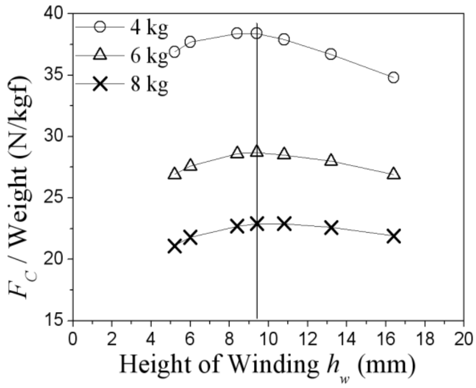


Fig. 2. Continuous load test pattern(duty type S5)



(a) Continuous thrust



(b) Thrust per unit weight

Fig. 3. Thrust calculation results according to coil height

2.3 Thrust per unit weight

If all design parameters are the same except for the winding height and current density, deriving the optimal model with maximum thrust per unit weight is quite straightforward.

Fig. 3(a) shows the variation of the continuous thrust as a function of the height of winding.

For the current density of each model, the current density of the basic model was applied. With increasing winding height, the air gap flux density is decreased, because both PMs (Permanent Magnets) interval draft apart. However, in this model, the thrust showed a greater increase as the winding electromagnetic force was increased. Fig. 3(b) shows the thrust per unit weight obtained for the experiment results of continuous thrust.

As presented in Fig. 3(a), as the winding height is increased, the continuous thrust is also increased, despite that the mover weight is heavier. Therefore, the maximum point of thrust per unit weight exists in the middle region. As indicated in this figure, for the basic model the winding height is 9.4(mm) with weight of 4-8(kg) including the mover and load

3. Design for Coil Temperature

A noteworthy finding in this paper is the change of the thermal characteristics according to variation of the winding height. The winding temperature rises if the current density is not changed, despite that the winding height is higher. Therefore, the thrust needs to be computed with recalculation of the current density in each model with different winding height. In this case, the optimal model would be derived at different points, because the thrust changes according to the winding height and thrust per unit weight.

3.1 Design process

Fig. 4 shows the optimal design process for coil temperature. The key point of this process is to compute the current density using a thermal transfer finite element analysis rather than assuming it based on experience. First, the limit of the winding temperature is determined and then a thermal transfer analysis is carried out assuming any value for the current density. The thermal transfer analysis is repeatedly performed by changing the current density until the calculated winding temperature reaches the predetermined limit of the winding temperature.

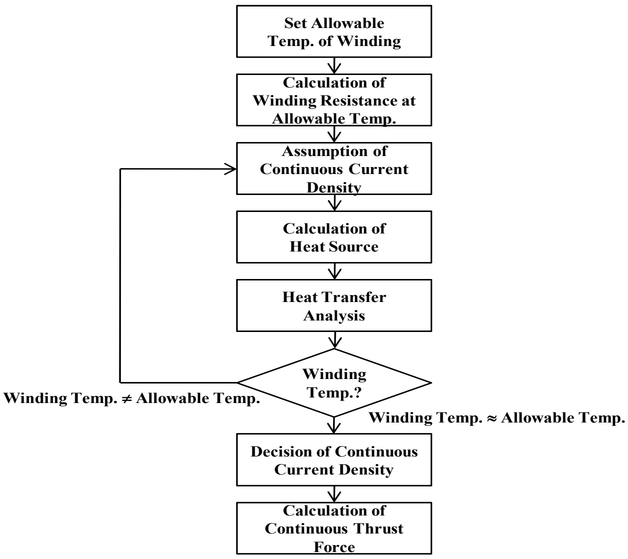


Fig. 4. Optimal design process for coil temperature

3.2 Thermal transfer analysis

The thermo field and static electric field were guided with the same geometry. So, the coefficient selection through the experiment, relatively, the exact thermal transfer analysis can be performed [10]. The convection heat transfer coefficients are the most difficult parameter to determine in the heat analysis. The convection heat transfer coefficient is not a material property. It is determined by the surface shape and the flow property which took place convection heat transfer [9]. Fortunately, the winding height, which is selected as one of the design parameters in this paper, does not change the convection surface shape or the flow property. Similarly, the convection heat transfer coefficient is not altered. The convection heat transfer coefficient was estimated by the experiment results of the basic model. Fig. 5 shows the distribution temperature of analysis model.

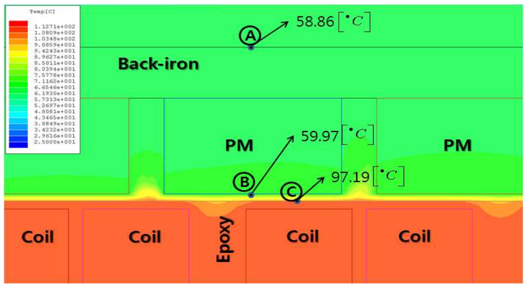


Fig. 5. Distribution temperature of analysis model

3.3 Consideration of the thrust winding temperature

The results of the thermal transfer analysis show that as the winding height was increased, the winding temperature rose when the same current density was applied, regardless of the winding height. The cooling effect is decreased because greater winding height is accompanied by the drawback of radiating heat. The continuous current density was recalculated until the winding temperature no longer exceeded the limit according to the winding height. Fig. 6 shows the result.

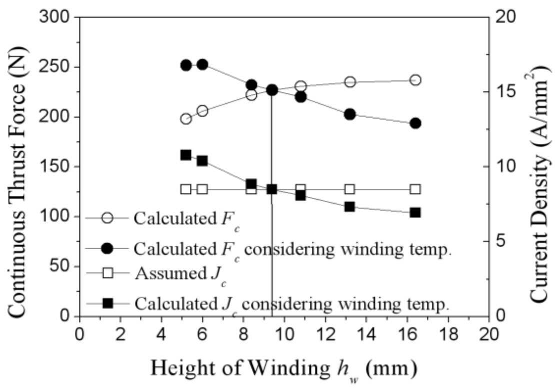


Fig. 6. Continuous thrust considering winding temperature

In the case without considering winding temperature, thrust was increased with higher winding height. However, in the case of considering winding temperature, the results show that lower winding height provides more thrust, as presented in Fig. 6. This means that as the winding height is decreased, the heat transfer characteristic is accordingly improved and higher current density is allowed.

3.4 Comparison of thrust per unit weight

Without consideration of the winding temperature the optimal model is equivalent to the basic model, where the winding height is 9.4(mm), as seen in Fig. 3(b). However, as the winding height is decreased, the thrust per unit weight was increased when winding temperature is taken into account, as seen in Fig. 7. As a result, the winding height of the optimal model must be lower than that of the basic model

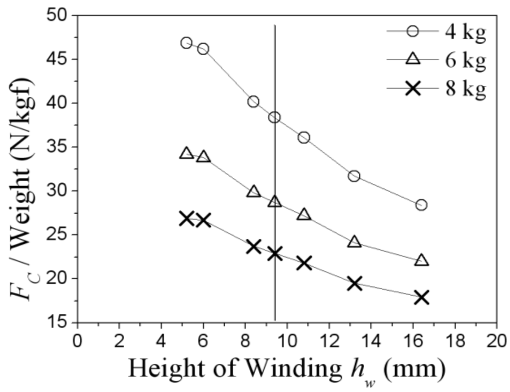


Fig. 7. Thrust per unit weight by considering the temperature rise

4. Comparison of Experiment Results with Analysis results

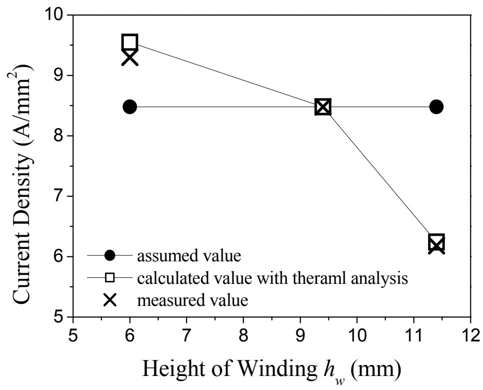
Three models with different winding heights were manufactured and the experimental results were compared with the analysis results.

4.1 Specifications of the Manufactured Model

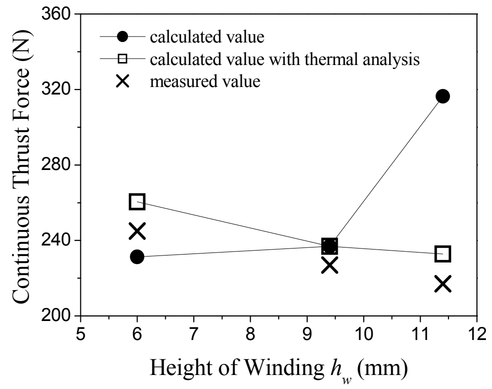
All design parameters were equally applied to the three models but the height of the winding and the number of turns was varied, as presented in Table 2, in order to acquire a reasonable thrust-velocity. The winding heights (h_w) of the models are as follows: basic model 9.4(mm), model B 11.4(mm), and model C 6.0(mm).

Table 2. Principal Specifications

Item	Model C	Basic Model (Model A)	Model B	Unit
Thickness of PM (t_m)	7.5	7.5	7.5	mm
Height of Winding (h_w)	6.0	9.4	11.4	mm
Width of Winding (w_w)	7.5	6.0	9.0	mm
Number of Turns	116	107	194	turn
Diameter of Coil	0.6	0.7	0.7	mm
Back – EMF Constant (k_E)	32.5	24.2	31.6	V• s/m
Thrust Force	93.6	69.7	91.0	N/A



(a) Comparison of current density



(b) Comparison of continuous thrust

Fig. 8. Comparison of measured and calculated values

4.2 Comparison of test results and analysis results

The current density 8.48(A/mm^2) which was obtained from the continuous load test when the thrusts of model B and C were calculated. The continuous thrusts of model B and C were calculated to be about 33.3% higher than that of the basic model. However, method of the thermal analysis in this work, model B, where the winding temperature was maintained at the allowable temperature was calculated, yielding a current density of 6.24(A/mm^2). This is lower than that of the basic model by about 26.4% and the continuous is decreased about 1.7% as a 233(N).

For model B, the continuous current density in the continuous load test was 6.18 (A/mm^2) and the continuous thrust was 217(N). That results of test drew same conclusion with this paper that estimated continuous current density 6.24(A/mm^2), 233(N) through a thermal analysis. In other words, there was a large discrepancy between the original design and the practical experiment. In the case of the conventional design without consideration of the winding temperature, it is expected to be increased by more than 33.3% relative to the existing model A. However, the practical experiment showed a reduction of 4.4%.

This result clearly told that if current density was not recalculated without design condition transformation at the design phase while heat transfer characteristics of machine is transforming with design condition transformation, it is possible to obtain incorrect results. In accordance with the results of this paper, to increase thrust, the winding height was designed to be low with recalculation of the continuous current density. In reality, two case of result in the continuous current density, the continuous load test were in agreement after testing model C with winding height of 6.0(mm) as 9.55(A/mm^2), 9.30(A/mm^2). Contrary to the results of thrust calculation without consideration of winding temperature, the continuous thrust of model C was expected to be reduced relative to that of basic model A, but the results obtained from a thermal analysis turn out to be increased above 9.7%. There was increase an increase in the results of the practical experiment of more than 7.9%. Mover weight also was reduced compared to the existing model A by approximately 21.1%. This is largely due to the winding height being calculated at low. Lastly, the material cost of the machine could be reduced as better result. If the winding height can be designed to be low, it better results can be expected. However, instability is also possible because mechanical rigidity may be reduced. Hence, a height of 6.0(mm) is considered appropriate based on current manufacturing technology.

Table 3. Comparison of Measured values and Calculated values

model	h_w (mm)	Calculated Value		Calculated Value Considering Winding Temperature		Measured Value	
		Jc (A/mm^2)	*Fc* (N)	*Jc* (A/mm^2)	*Fc* (N)	*Jc* (A/mm^2)	*Fc* (N)
C	6.0	8.48	231	9.55	260	9.30	245
A	9.4	8.48	237	8.48	237	8.48	227
B	11.4	8.48	316	6.24	233	6.18	217

If the continuous thrust is calculated with only a FEM analysis in terms of magnetic field, as in the conventional approach, at the design phase, a change of design would be tried such as increasing the size of the permanent magnet. This would be necessary because functional improvement could not be expected from the original model. This would involve trial and error without performing a thermal analysis.

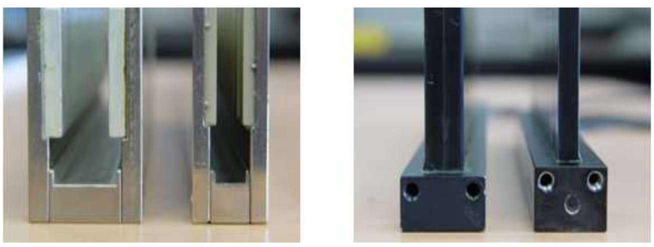


Fig. 9. Stator and mover of model B and C

Table 4. Test results and Specifications of Each model

Item	Model C	Base Model	Model B	Unit
Heights of Winding (h_w)	6.0	9.4	11.4	mm
Continuous Current Density (*Jc*)	9.30	8.48	6.18	A/mm^2
Continuous Thrust Force (*Fc*)	245	227	217	N
Mass of Mover	1.5	1.9	2.3	kg
Continuous Current	2.62	3.26	2.38	A
MMF(Magneto-Motive Force) per Winding	303.9	348.8	461.7	AT

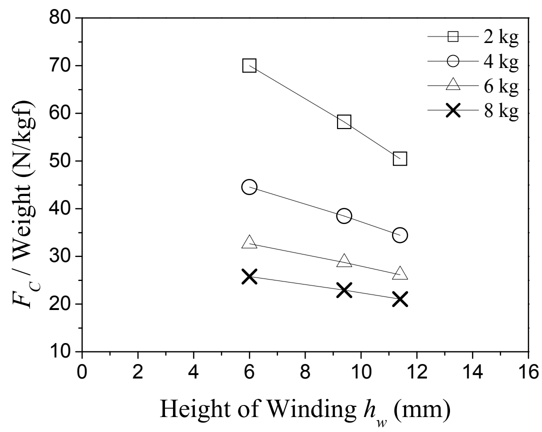


Fig. 10. Thrust force per unit weight of actual model

5. Conclusion

This paper dealt with the optimal design of a coreless PMLSM with consideration of rising winding temperature. Through the results of thermal analyses and tests, the heat release characteristics were found to vary according to the winding height of the coreless PMLSM. Contrary to the optimal model yielded by the conventional design method when the winding temperature is considered, it is proved that minimizing winding height is optimal. When the method presented in this paper is applied, the thrust can be increased and the production process can be easily simplified.

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