Rapid Eddy Current Loss Calculation for Transverse Flux Linear Motor

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***Abstract*—Transverse Flux Linear Motor (TFLM) is getting to be widely used in low speed and high power systems. For easy and rigid fabrication, solid core is more useful than laminated core, but core losses are increased, which makes efficiency decreased. Estimating core losses and selecting core types are important in design process to make a compromise high efficiency with effective manufacturing. Therefore, this paper proposes a rapid eddy current loss calculation method for Transverse Flux Linear Motor. The calculation is carried out with the aid of three dimensional Equivalent Magnetic Circuit Network Method (3D EMCN) and 2D Finite Element Analysis Method (FEM). Since the analysis of TFLM is a truly 3D problem, 3D EMCN is used to calculate magnetic field as a source of eddy current. Then 2D FEM is used to calculate eddy current loss rapidly with equivalent analysis models. The usefulness of the proposed method is discussed by comparing the calculation results with the results by another core loss calculation method and experiment.**

Keywords-Eddy current loss; 3D Equivalent Magnetic Circuit Network; Transverse Flux Linear Motor

I. INTRODUCTION

Transverse Flux Linear Motors (TFLMs) have a number of useful features distinguished from other motors [1]. TFLM offers a very high force density, and it is suitable for direct drive applications because the mover can produce high flux density in air gap compared with other motor types. This high flux density, however, can cause considerable core losses, which affect the motor performances. Laminated core is generally used because it is the best solution to reduce core losses, but rigid fabrication with laminated core is more difficult than with solid core. Therefore in the design process, expecting core losses and selecting core type are important to find a compromise point between high efficiency and effective manufacturing.

The core losses are usually classified into three types; hysteresis loss, eddy current loss (or classical loss), and, anomalous loss. Among these three losses the eddy current loss is most influenced by flux density, frequency, and even lamination thickness [2]. Therefore, the authors in this paper are interested in calculation of eddy current loss for TFLM.

The problems of eddy current and the losses have been treated by several researchers [3-6]. They try to calculate core losses more precisely with their own assumptions and the results are verified by comparisons of calculated results from each analytical method or each analysis model, or by comparison between calculated and measured flux densities. In other words, there are several assumptions for the simulations, and there are indirect parameter comparisons for the measurement. These indicate that the both computation and measurement of core losses are quite challenging tasks. Furthermore the computation time is several hours or days even for small analysis model (except the case of small segments). This is very troublesome especially on the design stage.

Therefore, this paper proposes a rapid practical method to estimate eddy current loss of TFLM. The specific objective model is a permanent magnet (PM) type TFLM with stator having both laminated and solid cores. The calculation by the proposed method is carried out with the aid of 3D Equivalent Magnetic Circuit Network Method (3D EMCN) [7] and 2D Finite Element Analysis Method (2D FEM). Since the analysis of TFLM is a truly 3D problem, 3D EMCN is used to calculate magnetic field as a source of eddy current. Then 2D FEM is used to calculate eddy current loss rapidly with equivalent analysis models. The proposed method focuses on rapid estimation of eddy current losses rather than precise calculation.

In order to verify the usefulness of the method, another core loss calculation method using core loss data [8] is also dealt here. The eddy current loss calculated by the proposed method, the core loss calculated by the method of [8], and some experimental results are compared, and discussed.

II. ANALYSIS MODEL

Fig. 1 and Fig. 2 show configurations of a PM type TFLM fabricated to test its application to a high power transportation system. The mover has solid core for rigid fabrication, and both PM and armature coils are in the mover. The stator has both laminated and solid cores as shown in Fig.2 to find a compromise point between high efficiency and effective manufacturing.

The principle of force generation of objective model is shown in Fig. 3 which is the $\overline{AA'}$ section of Fig. 1. In the mover poles, the two magnetic polarities by PMs, N and S, are changed to one polarity, N or S, by offset one polarity against the polarity of current coil. Therefore, when the polarity of current coil is N, ideally there is only polarity N in the mover as shown in Fig. 3. Alternating current functions as a switch turning on and off the mover polarity, therefore, mover and stator generate the total thrust in one direction.

Table 1 shows the specifications of the PM type TFLM, and the Figs. 4 and 5 are the measured magnetic characteristics of the materials. The B-H curve data shown in Fig. 4 are used for

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magnetic field analysis, and the core loss data shown in Fig. 5 are used for core loss calculation by the method of [8].

III. Calculation Methods of Core Losses

In this paper, the only eddy current loss calculation method is proposed. However, in order to verify the usefulness of the method, the core loss calculation method of [8] is dealt, which is quite precise method because of using measured core loss data so that it is not able to be used in design process.

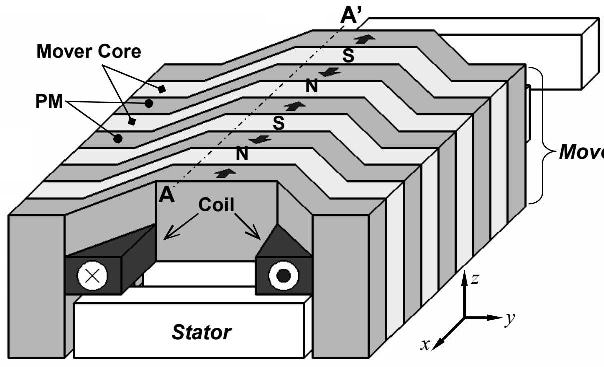


Fig. 1. A configuration of a PM type transverse flux linear motor

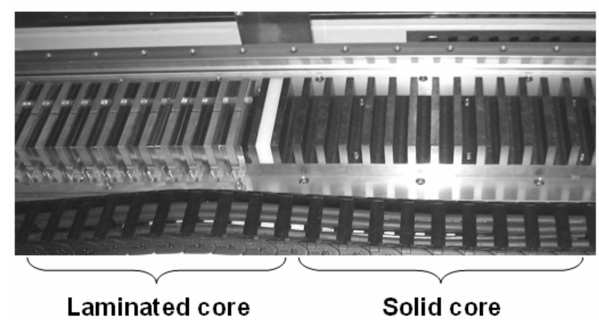


Fig. 2. Fabricated stator with both laminated and solid cores

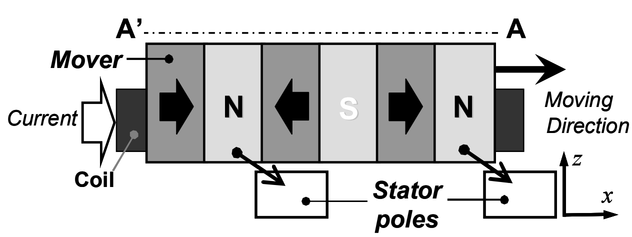


Fig. 3. Principle of force generation

TABLE 1. Specifications per One Phase

Stator	***Material***	SM490A (Solid core) S20C (Laminated core)
Mover	***Material***	SM490A (Solid core)
	PM	Br =1.2 , μ_r =1.05
	No. of turn	160 turns
	Rated Current	31.25 A
	No. of Pole	20 (Iron), 19 (PM)
Air gap Length		2 mm
Rated Speed		2m/s (50Hz)
Rated Thrust		10,000N (by 4 phases)

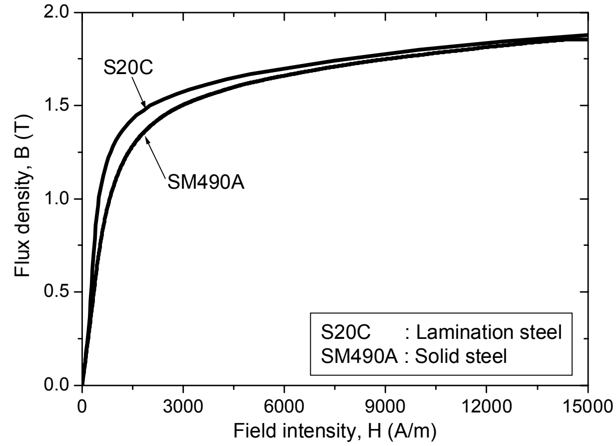
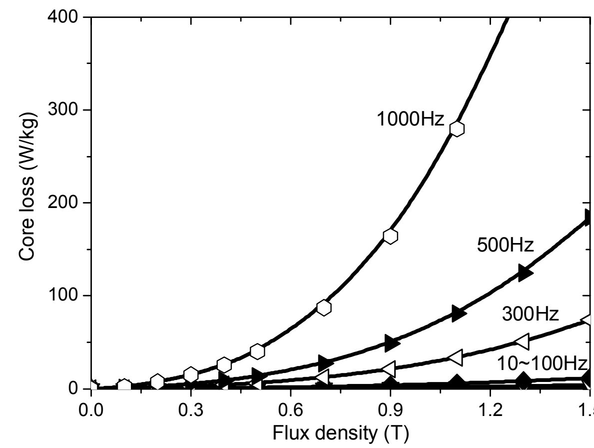
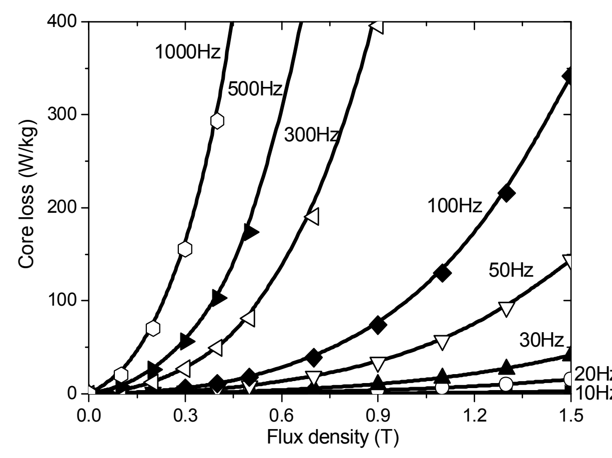


Fig. 4. B-H curve characteristics of magnetic materials, S20C and SM490A



(a) Core loss data of S20C
(sample volume: 30× 150× 0.5 mm^3, long strips)



(b) Core loss data of SM490A
(sample section area and inner diameter: 20× 19mm^2, 100mm, ring core)

Fig. 5. Core loss data of materials according to frequency and flux density

A. Core loss calculation method of [8]

This method is only reviewed very briefly here for understanding when the results calculated by this method are compared with the proposed method.

Fig. 6 shows the flowchart for the core loss calculation of [8]. The temporal and the spatial variations of the magnetic flux density waveforms are calculated by FEM or 3D EMCN, and in this paper 3D EMCN is used. Discrete Fourier Transforms (DFT) is used for the frequency analysis of the magnetic flux density at each element of the meshed analysis model. The core losses w_e at each element are calculated from the summation of the losses $w(Bv, vf)$ according to frequencies using DFT results and core loss curves such as Fig.5. Finally, the total core loss is obtained by the summation of the core losses in all elements.

B. The Proposed method for eddy current loss calculation

In order to rapidly calculate eddy current loss of TFLM which has 3D flux paths, both 3D and 2D field computations are used. Fig. 7 shows the proposed method with three-step blocks. First, the magnetic field is calculated by 3D EMCN according to movement of the mover, and then the flux density variation of each element converts to field intensity which is used as source field inducing eddy current. The eddy current losses are computed by harmonic field analysis using 2D FEM.

Before detail explanation for the three steps, the basic assumptions are presented below.

1) Basic Assumptions

Through the rapid calculation process, there are the basic five assumptions as follows:

i) steady state operation is only considered.

ii) both solid and laminated cores are treated as a homogeneous conducting medium with isotropic permeability, and iron saturation is considered.

iii) a center element of divided regions in analysis model can be the representative element to calculate flux density variation according to movement of mover.

iv) field intensity converted from flux density is dealt as the source inducing eddy current, and the fundamental component is only used.

v) field source and eddy current have three components in x, y, and z direction, and they are orthogonal and independent each other.

2) Step1-3D Magneto Static Analysis

First of all, magneto-static field computation is performed by 3D EMCN, which not only gives accurate results, but also is the faster calculation method in comparison with 3D FEM [7]. The analysis model is meshed in several hundred thousand hexahedron elements as shown in Fig. 8 (a), which is y-z coordinate view side in Fig. 1. The mover is moved during one period of input current. In this step, the flux density variation of each element is calculated for steady state operation.

3) Step2-Data Processing

After magneto static analysis, the analysis model is divided into a few regions considering main flux path and core saturation. In the case of the object TFLM model in this paper, the analysis model is divided into 17 regions as shown in Fig. 8 (b). Instead of using total elements of 3D analysis model, the center element of each divided region is representatively used to calculate the field intensity as the source inducing eddy current in the region.

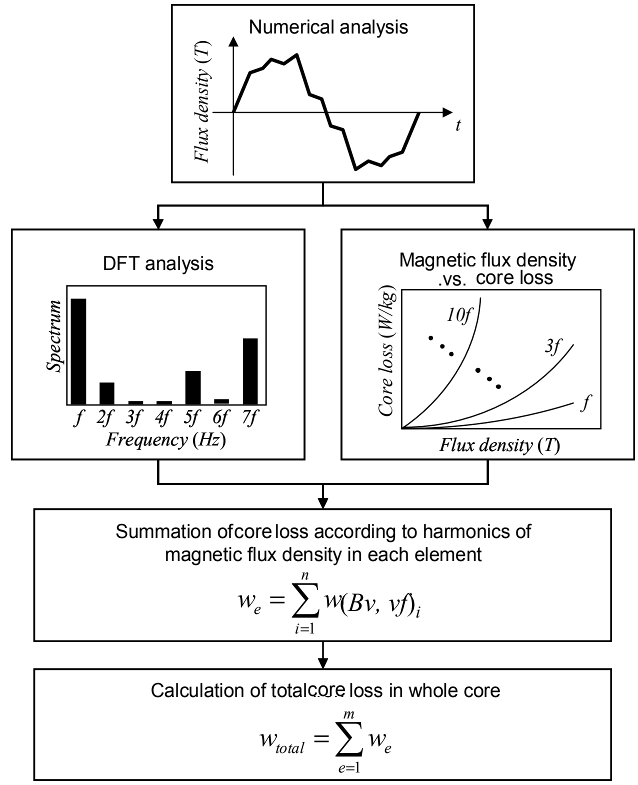


Fig. 6. Flow chart for core loss calculation by the method of [8]

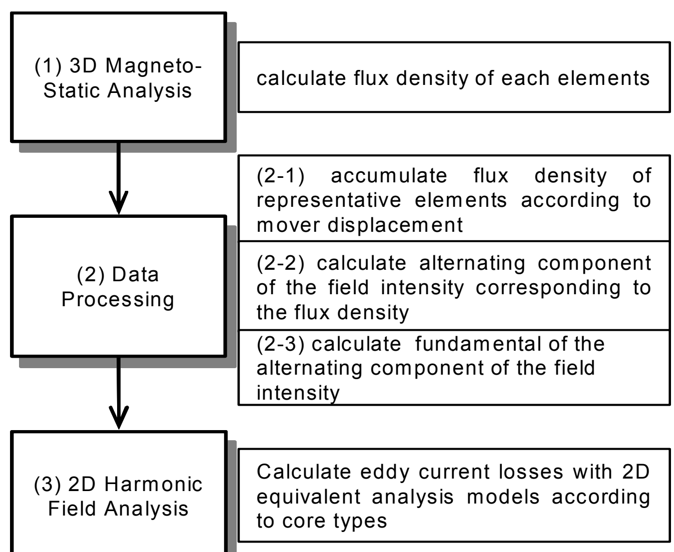


Fig. 7. The proposed eddy-current-loss calculation process

a) Accumulation of flux density variation

Actually, the flux density variation of elements was already calculated in the first step. In this step, the flux density of each center element in divided regions is selected from the calculated results. As using a rectangular coordinate, flux density is separated into three components, x, y, and z as shown in Fig. 9(a) where Bx, By, and Bz are the x, y, and z components, respectively.

b) Calculation of alternating component of field intensity

To calculate source of eddy current, the flux density variation calculated in step 3 is converted to the field intensity. The conversion is achieved by one-to-one correspondence using B-H characteristic data of magnetic material used in magneto static analysis. Then, the alternating components are separated from the calculated field intensity as shown in Fig. 9(b), and used as the source component of eddy current.

c) Calculation of fundamental of field intensity

The fundamental of alternating components of field intensity can be obtained by Fourier transformation. As an example, at the 100% of magneto-motive force (mmf) of coils, the alternative flux density and field intensity, and the fundamental of field intensity of the representative element in first region in Fig. 8(b) are shown in Fig. 10. Although the flux density variation has triangular shape in first half period and almost rectangular shape in last half period, the corresponding alternating component of field intensity has different shape, and the total harmonic distribution (THD) is about 10%.

The all THD of field intensity for dominant component in each representative element is under 15%, and the eddy current losses by the harmonics cannot be summed by algebraic equations because the characteristic of magnetic material is not linear. Therefore, the fundamental component is only considered as the source for eddy current loss calculation.

4) Step3-2D Harmonic Field Analysis

The formulation chosen for the stator and mover cores is T-Φ, which has the differential equation in [3]. The difference from the reference equation is that the work in this paper is performed by 2D harmonic field analysis, and considered core saturation.

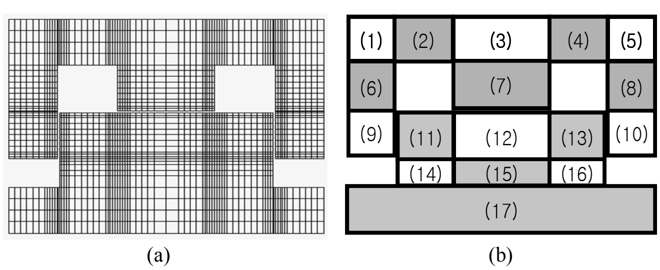


Fig. 8. 3D Magneto-static analysis by 3D EMCN; (a) 3D-meshed model with about 480,000 elements, (b) 17-divided regions according to remarkable change of magnetic flux path

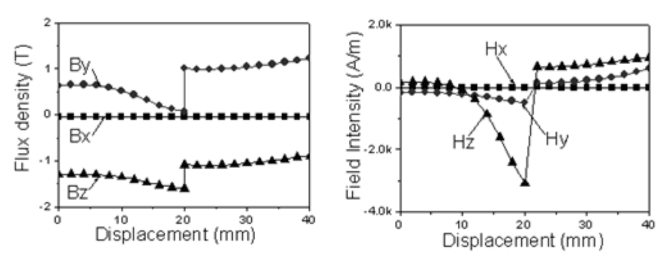


Fig. 9. Data processing; (a) flux density variation according to mover movement, (b) alternating component of field intensity

Although 2D analysis model and 2D field analysis are used to calculated eddy current loss, laminated and solid cores and 3D components of sources are considered by separated 2D models as shown in Fig. 11. Each region separated in step2 is modelled into three kinds of 2D analysis models. Fig. 11 (b) and (c) is the example in the case of solid core. The three planes, Pxy, Pyz, and Pxz are the boundary planes of the separated region, and the sinusoidal Hx, Hy, and Hz are the sources which go through perpendicular to each plane.

In the case of laminated core, the length of laminated directional sheet is changed such as from (SD) model to (L1) or (L2) model as shown in Fig. 11 (a). Except the analysis model, the other concepts for analysis are the same as solid core case. In the case of object TFLM model in this paper, the number of total 2D analysis models is 58 including mover, and laminated and solid stator cores. Fig. 12 shows the equi-potential lines and current density distribution after 2D FEA.

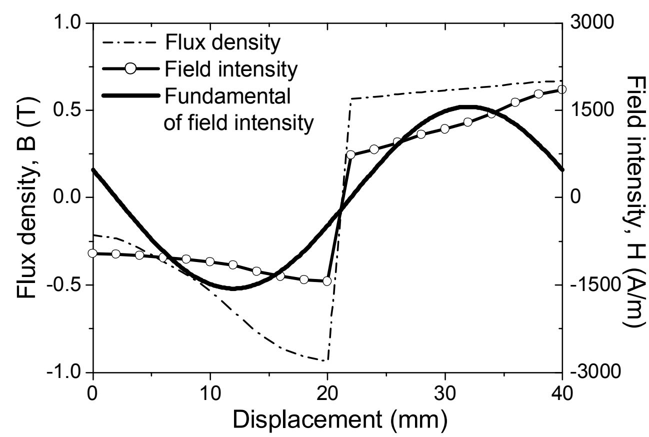


Fig. 10. Flux density, field intensity, and the fundamental of field intensity variation of the representative element in the first region in Fig. 4 (b)

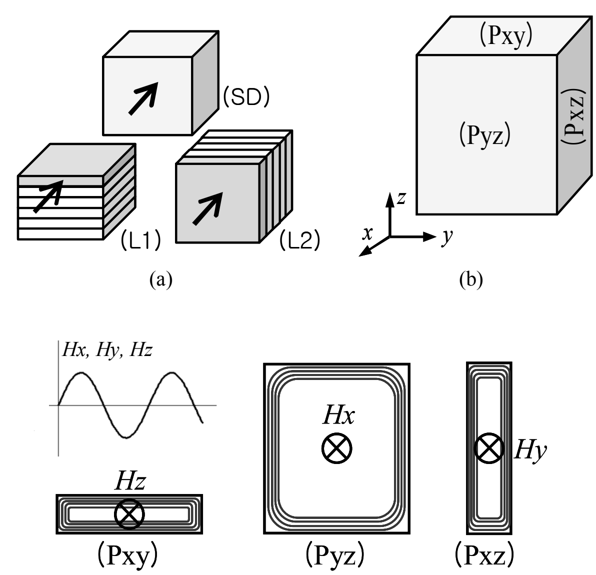


Fig. 11. The concepts of 2D-equivalent analysis models and mmf waveform for 2D harmonic field analysis of each 3D divided region

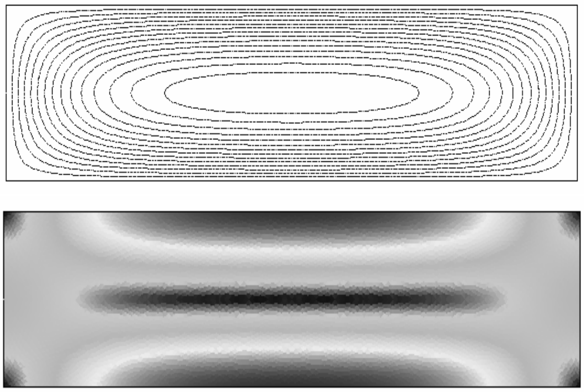


Fig. 12. 2D harmonic field analysis results; (up) equi-potential line, that is, eddy current flow, (down) eddy current density distribution

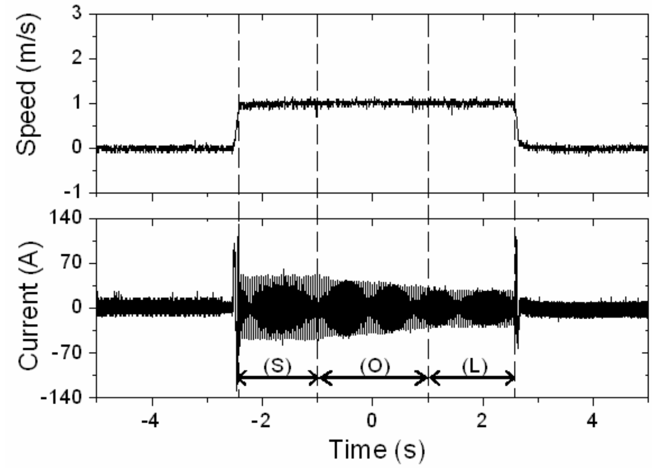


Fig. 13. Measured current variation according to mover position (No load condition)

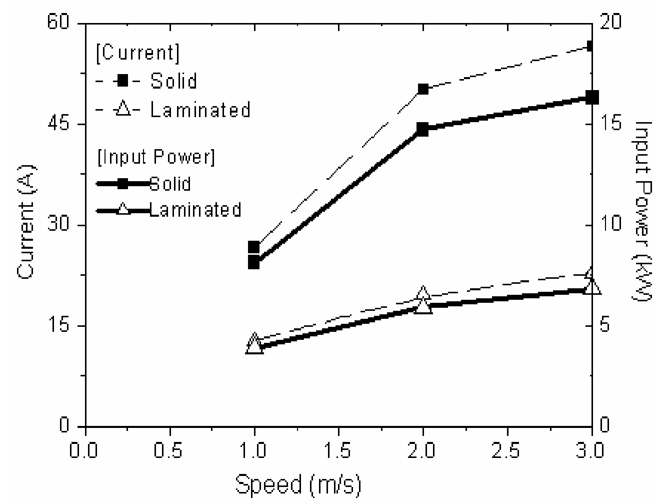


Fig. 14. Current and input power variation according to mover speed (No load condition)

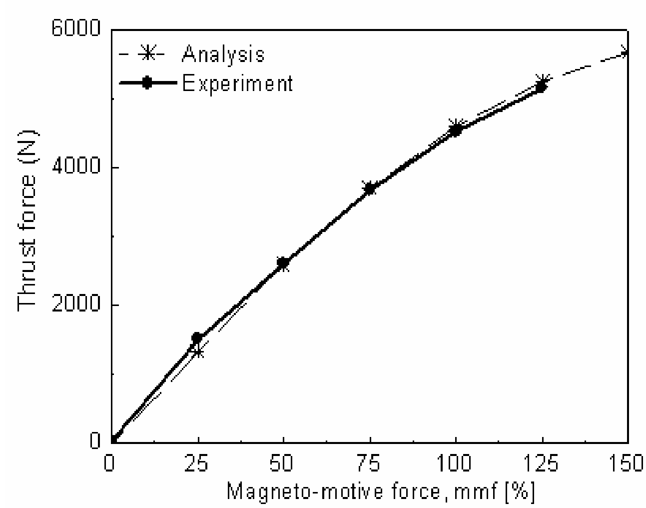


Fig. 15. Average static thrust force according to mmf variation

IV. Experiment and Analysis Results

To verify the accuracy of a calculation method of eddy current loss, usually indirect parameters such as total core loss and temperature are measured and compared quantitatively with the calculated losses. Since the proposed method focuses on rapid estimation of eddy current losses rather than precise calculation, however, any quantitative comparison of experiment and calculated results is not dealt here. Only the aspect of losses according to input current and frequency is discussed with experimental data.

Although, precision is not important for this method, a regular aspect is required to be used in design process. Moreover, it also needs to estimate approximate core loss by the computed eddy current loss. Therefore, the eddy current loss calculated by the proposed method is compared with the core loss calculated by the method of [8], and the usefulness of the proposed method is discussed.

A. Experiment Results

Fig. 13 and Fig. 14 show the experiment results with the TFLM as shown in Fig. 1. The measured current in Fig. 13 shows the different characteristics between laminated and solid cores. When the mover goes at the constant speed from on the solid core stator through on the laminated core stator, the current is changed from (S) to (L). The (O) is the span when the mover is over both laminated and solid cores.

For the same thrust, current variation according to mover speed and core type is shown in Fig. 14. Since the input voltage is the same, when the mover goes through on solid core stator, the output power is almost two times of the output power when the mover goes through on laminated core stator. Considering the constant speed and the same mover and mechanical guide assemblage, it is estimated that the most part of the loss is due to core losses. This experiment result shows indirectly the fact that eddy current losses can severely increase depending on core type.

The comparison of calculated and measured average static thrusts in Fig.15 shows the accuracy of the analysis method, 3D EMCN, which is used for both core loss and eddy current loss calculation.

B. Analysis Results

The specification for analysis is the same as Table I. In the case of experiment as shown in Fig. 14, input current is changed for the constant thrust depending on stator condition, but in the case of analysis input current is the same as the rated current in Table I. The analysis models are two depending on stator core type; one is the lamination core stator model, and the other is the solid core stator model. The mover parts of these two models are the same as solid core.

1) Core loss calculation results

Fig. 16 shows total core loss calculated by the process shown in Fig. 6 for four cases listed in Table 2. The CASE-I is that the core loss is calculated by using all elements of analysis model shown in Fig. 8 (a), and considering from fundamental to 20th harmonics of magnetic flux density. The result of this case can be compared to experimental result. The CASE-II is that the core loss is calculated by using all elements of analysis model as CASE-I, but only fundamental component of magnetic flux density is considered. The CASE-III is that the representative elements of each 17-divided-region shown Fig. 8 (b) are only considered to calculate core loss, and from fundamental to 20th harmonics of magnetic flux density are used. The CASE-IV is the same as CASE-III except that only fundamental component of flux density is considered. The result of this last case, CASE-IV, is compared with the result of eddy current loss calculation by the proposed method.

From the Fig. 16, it is evident that the total core loss is devaluated depending on considered number of elements and harmonics. However, the aspect is uniformed as shown in Table 3. The ratio of core losses of each case to core loss of CASE-I is averaged for speed, and the ratio is similar between lamination core stator model and solid core stator model for all cases. Therefore, the core loss of CASE IV can be considered about 40 to 50% of the core loss of CASE I in this kind of TFLM model. Fig. 17 shows comparison of core loss calculated in the condition of CASE-IV. The 100% of mmf is for rated current input.

2) Iron loss calculation results

Fig. 18 shows the comparison of peak values of field intensity fundamental components, which are input mmfs of each region for 2D harmonic field analysis. Although only the material of stator core is different in the two analysis models, the mmfs of both mover and stator regions are different. It is because the permeability of the two materials is different, and the mmf of PM is changed, which makes total mmf changed.

This fact indicates that the total core loss is changed by not only stator part but also mover part despite of only stator core difference. Therefore, the total loss is compared.

Fig. 19 shows the eddy current loss calculation results obtained by the proposed method. Each resistivities of materials are calculated in proportion to the value of similar material listed in Table 4. In the case of S20C, the resistivity is assumed as 36.8 μΩ-cm because the characteristic of the material is between PN18 and PN20, In the case of SM490A, the resistivity is assumed as 16 as the lowest value of data sheet because of non Si solid core.

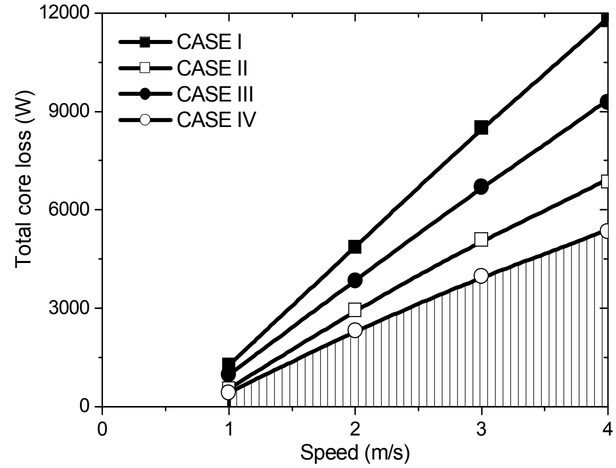


Fig. 16. Comparison of core loss calculation results according to cases listed in Table 2. (lamination core stator model at input current 31.25A)

TABLE 2. FOUR CASES FOR CORE LOSS CALCULATIONS

	Elements used for core loss calculation	Harmonics used for core loss calculation
CASE I	All Elements	$1^{st} \sim 20^{th}$
CASE II	All Elements	1^{st}
CASE III	Representative Elements	$1^{st} \sim 20^{th}$
CASE IV	Representative Elements	1^{st}

TABLE 3. AVERAGE RATIO OF CORE LOSSES OF EACH CASE TO CORE LOSS OF CASE I FOR SPEED

	Lamination core stator model	Solid core stator model
CASE I	100%	100%
CASE II	59%	58%
CASE III	79%	81%
CASE IV	46%	46%

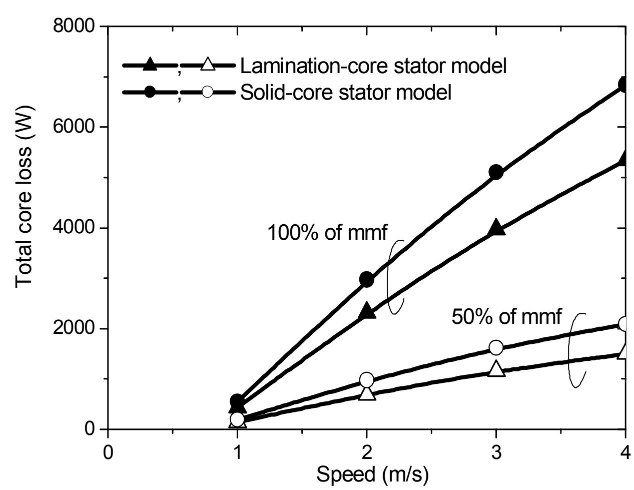
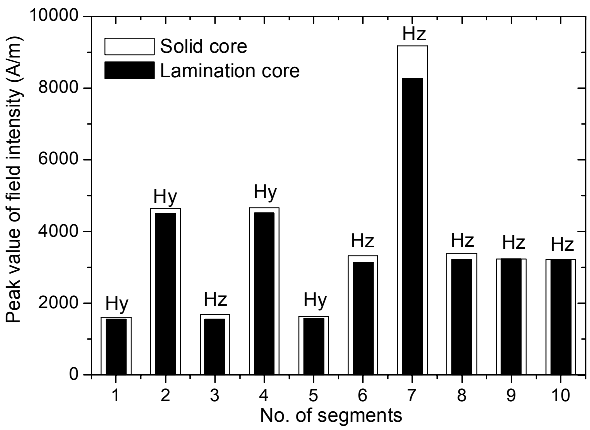
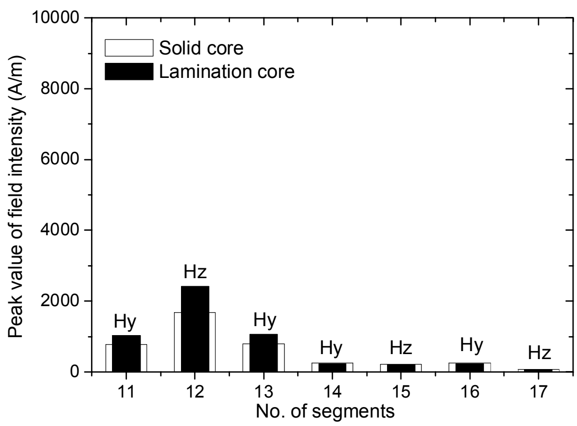


Fig. 17. Core losses calculated by the process shown in Fig. 6 (CASE IV)



(a) mover regions



(b) stator regions

Fig. 18. Input mmfs of each region for 2D harmonic field analysis

When the eddy current loss shown in Fig. 19 is compared with core loss shown in Fig. 17, the value of eddy current loss is almost half of the value of core loss at rated speed 2m/s, and this is very acceptable considering that the eddy current loss and hysteresis loss are almost the same at the low speed. Moreover the aspects of the two graphs according to speed is very similar so that core loss can be expected by the eddy current loss calculated by the proposed method.

V. DISCUSSIONS

In this paper, the rapid analysis method is proposed to calculate eddy current losses in both the solid and laminated cores of TFLM. Even though it cannot give accurate magnitude of core losses, it gives rapidly the acceptable aspect. The computation time is 40 minutes for the 3D magneto static analysis, under 30 minutes for data processing, and 20 minutes for the 2D harmonic field for the TFLM analysis model at one position. If the analysis is performed for several cases such as variable frequency and mover positions, the time for each case is less than one hour because there are many duplicate works.

It is quite fast considering the dimension of the analysis model. Furthermore, the acceptable aspect is verified by the comparison with the results calculated by other verified method. It will be useful to use it in the design process to estimate eddy current losses.

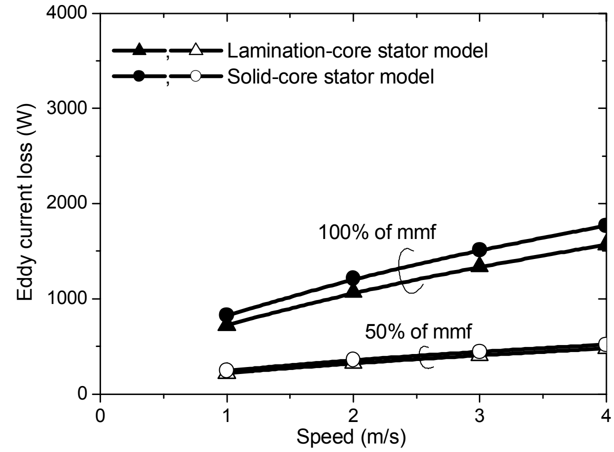


Fig. 19. Core losses calculated by the proposed method shown in Fig. 7

TABLE 4. TYPICAL MAGNETIC PROPERTIES

Grade	Assumed Density (g/cm^3)	Resistivity (μΩ-cm)	Core loss (W/kg) 50Hz	
			1.0T	1.5T
PN10	7.65	55	1.2	2.75
PN18	7.70	40	1.7	3.8
PN20	7.75	34	2.0	4.3
PH60	7.85	16	3.9	8.3

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