# Electromagnetic Analysis of Linear Magnetic Gears according to the Characteristics of their Flux-Modulation Poles

**Sung-Won Seo** [1], Gang-Hyeon Jang [1], Chang-Woo Kim [1], Ick-Jae Yoon [1] and Jang-Young Choi [1]

[1] Department of Electrical Engineering, Chungnam National University, Daejeon 34134, Republic of Korea

MT26 International Conference on Magnet Technology
Vancouver, Canada | 2019

CHUNGNAM NATIONAL UNIVERSITY
N.E.E New electrical Energy Lab.

## Abstract

*Magnetic gears (MGs) are energy converters that have recently received attention because of their advantages over conventional mechanical gears. Prior studies have focused on MGs without mechanical losses, and research on linear MGs has focused on tubular structures. In this study, we performed an electromagnetic analysis of simplified linear MGs based on the characteristics of their flux-modulation poles (FMPs) by presenting an optimal model of a simplified linear MG within the range of manufacture and analyzing its characteristics with three different FMP materials. In addition to comparing the electromagnetic characteristics analysis of each material, an equivalent stress analysis was performed. Finally, the proposed model was fabricated, and experimental verification was performed.*

## I. INTRODUCTION

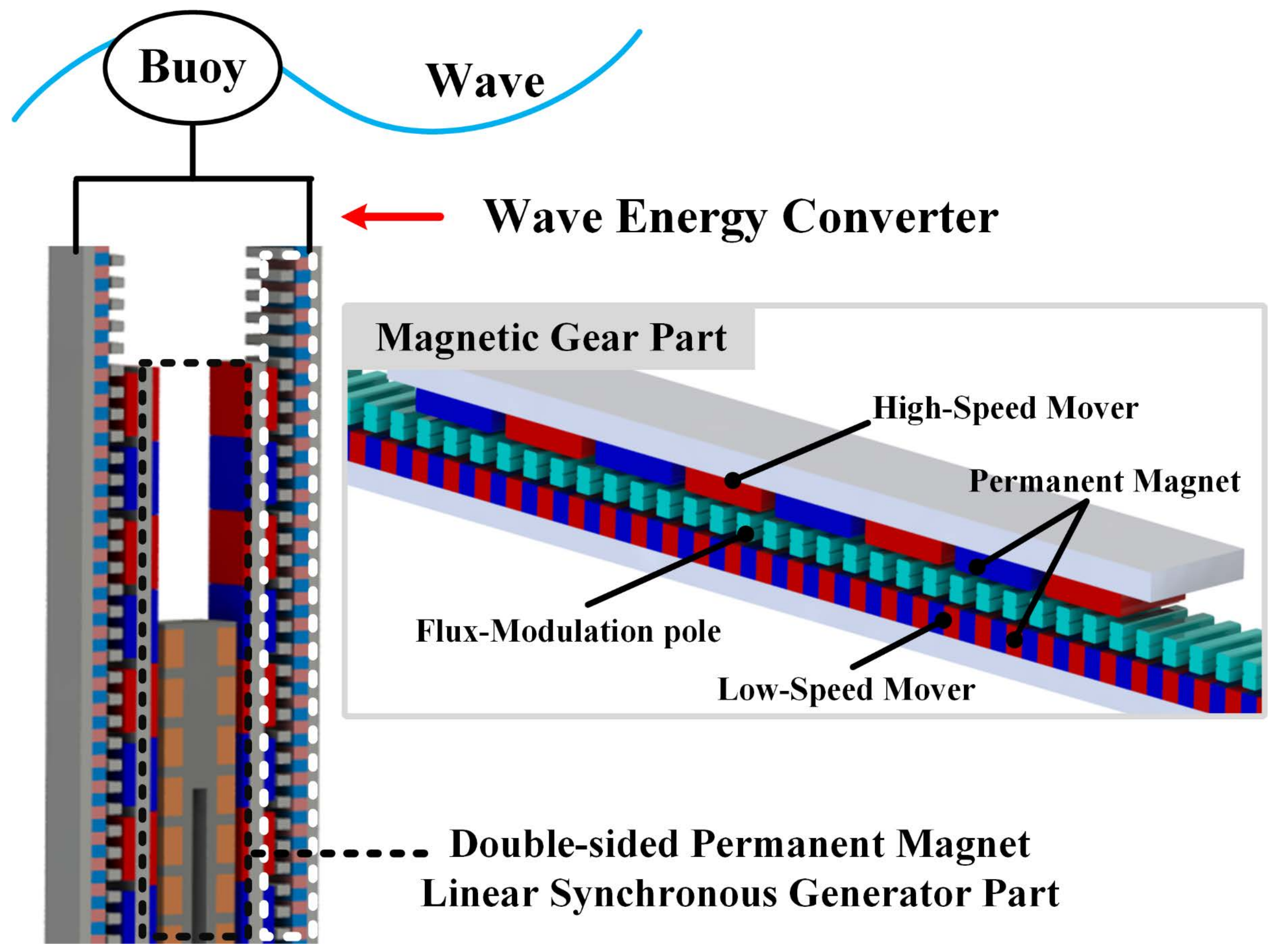

Fig. 1. Structure and concept of the wave energy converter system.

TABLE I. Specifications of the Linear Magnetic Gear

| | High-speed mover | Low-speed mover |
|---|---|---|
| *Total length* | 322 mm | 973 mm |
| *PM thickness* | 10 mm | 10 mm |
| *PM pole length* | 34 mm | 7 mm |
| *Number of pole pairs* | 4 | 23 |
| *Thickness of the FMP* | 9 mm | |
| *Stack length* | 30 mm | |
| *Number of FMP* | 27 | |
| *Gear ratio* | 5.75 | |
| *Rate speed of the HSM* | 1 m/s | |

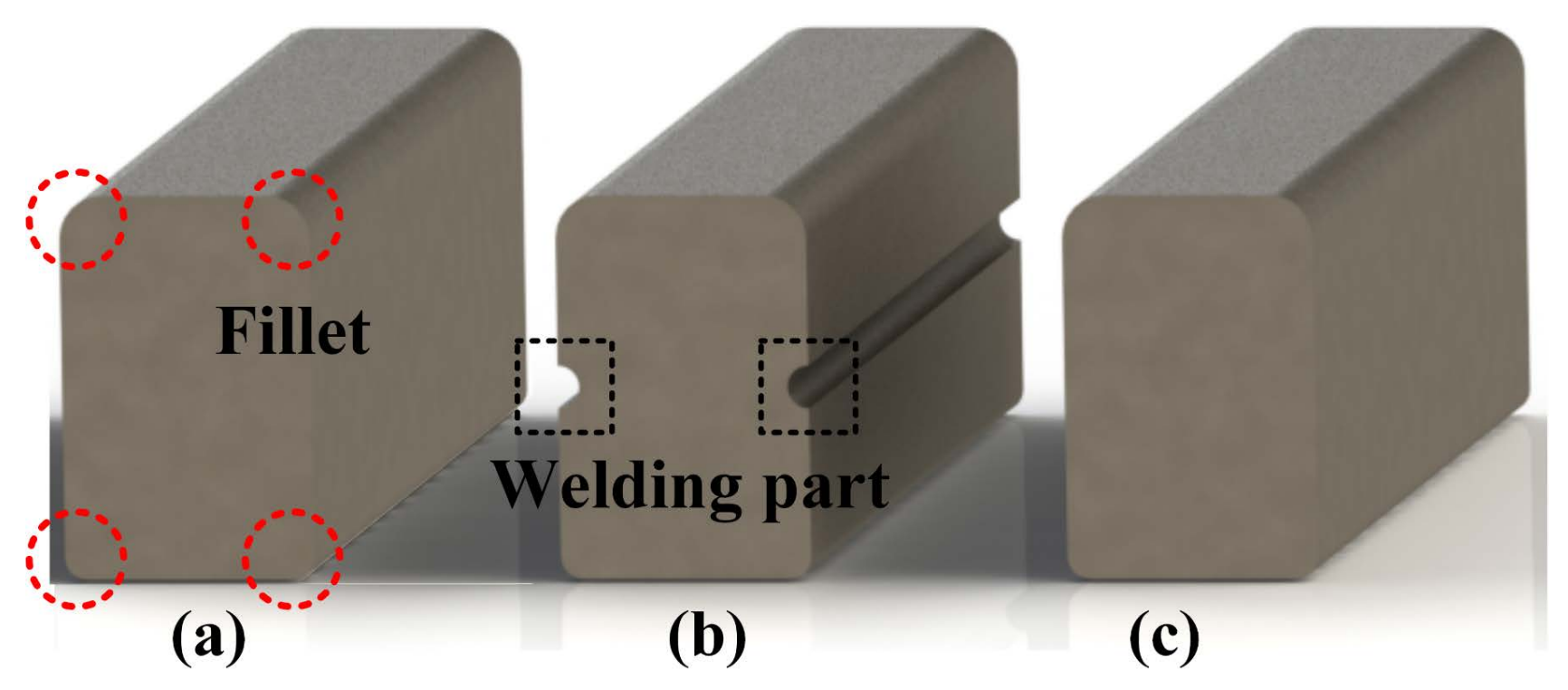

Fig. 2. Shape of FMP by material: (a) Iron, (b) 50PN470, and (c) SMC.

- ✓ In the case of MGs, power transmission through speed increase and torque amplification can be realized through a contactless mechanism using permanent magnets (PMs).
- ✓ Moreover, the use of high efficiency PMs can be extremely useful because they reduce the overall volume and weight.
- ✓ In this study, we performed an electromagnetic analysis of simplified linear magnetic gears (LMGs) based on the characteristics of their flux-modulation poles (FMPs).
- ✓ The performance of the LMG is highly dependent on the characteristics of the FMP and is greatly affected by electro-magnetic and mechanical losses when driven at high speeds.
- ✓ Therefore, considering the fillet effect and shape of the FMP, we proposed the optimal type of LMG by comparing the characteristics of the FMPs made of three materials: non-laminated core, laminated core, and soft magnetic composite (SMC) core .
- ✓ Fig. 1 shows the structure of a wave energy converter system with a buoy and an LMG.
- ✓ The specifications of the LMG are listed in Table I.
- ✓ Fig. 2 shows the FMP shape according to the material; although their shapes are identical, in the case of electrical steel (50PN470), welds due to stacking are included.

## II. STRUCTURE AND ANALYSIS COMPARISON OF THE PROPOSED LMG

- ✓ The criteria for analysis model selection were a total HSM length of 322 mm, considering manufacturing constraints, and four pole pairs. Therefore, the sizes of the FMP and LSM can be calculated as follows:

$$P_L = G_r \cdot P_H \qquad (1)$$

$$N_P = \left( {P_L}/{2} \right) + \left( {P_H}/{2} \right) \qquad (2)$$

- ✓ where, $P_H$ and $P_L$ are the numbers of poles in the HSM and LSM, respectively. $G_r$ and $N_p$ are the gear ratio and the number of FMPs, respectively.
- ✓ Further, the speeds of the HSM and LSM are determined by the gear ratio as

$$\omega_L = -\left( {G_r}/{\omega_H} \right) \qquad (3)$$

- ✓ where $\omega_H$ and $\omega_L$ are the rated speeds of the HSM and LSM, respectively.

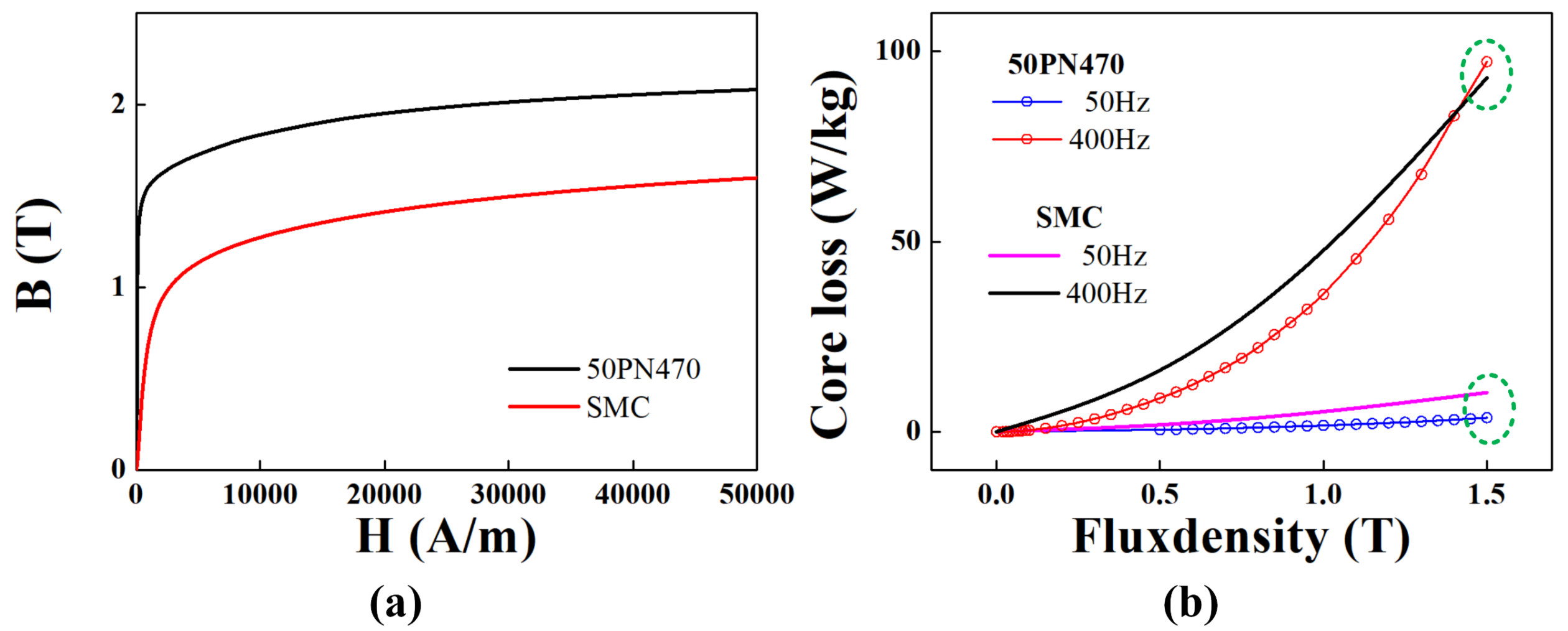

Fig. 3. Characteristic according to material: (a) *B-H* curve, (b) core loss data.

- ✓ Fig. 3 shows the B-H curve and core loss data of electrical steel and SMC cores. As shown in Fig. 3, the higher the frequency, the better the core loss, but the low permeability causes it to be easily saturated.

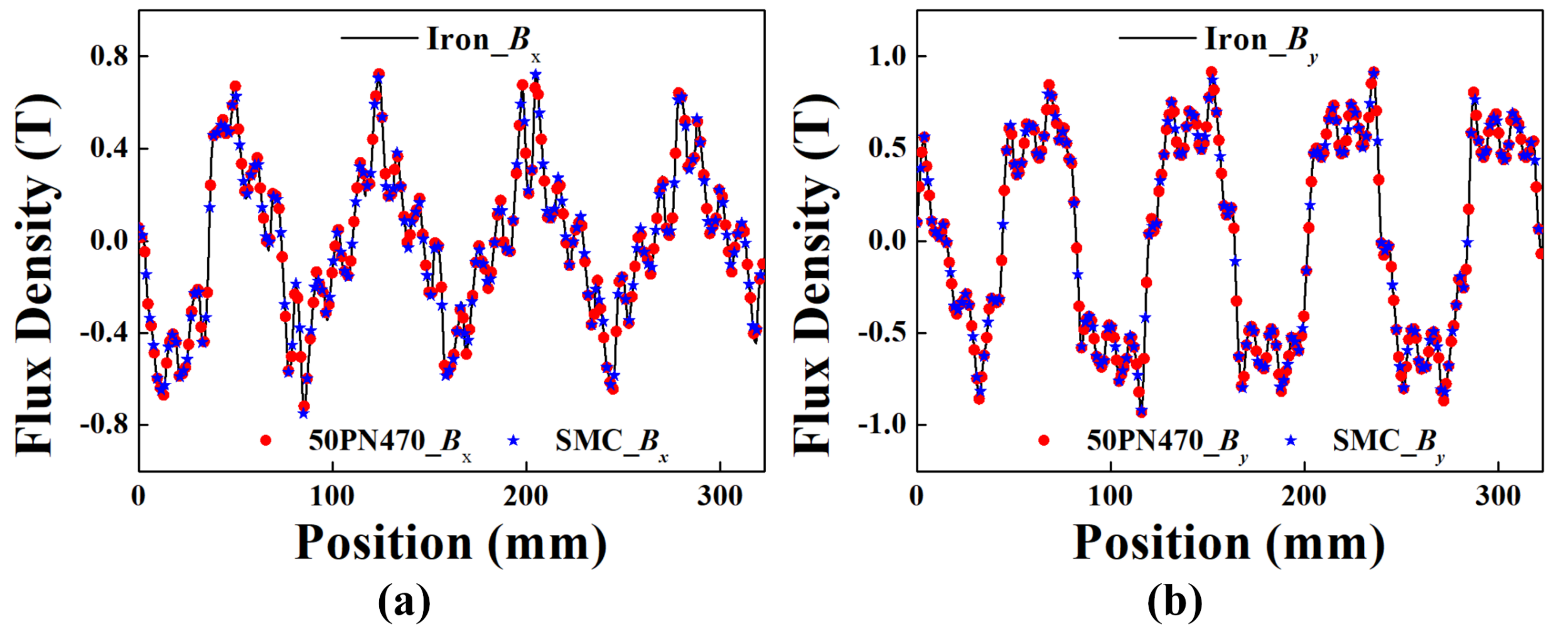

Fig. 4. Comparison of magnetic flux density distribution by material: (a) $B_x$ (b) $B_y$.

- ✓ Fig. 4 shows the distribution of magnetic flux density in the air gap between the HSM and FMP of each material, showing that they all have the same magnetic flux density.

## III. CHARACTERISTIC ANALYSIS AND EXPERIMENTAL COMPARISON BASED ON FMP MATERIAL

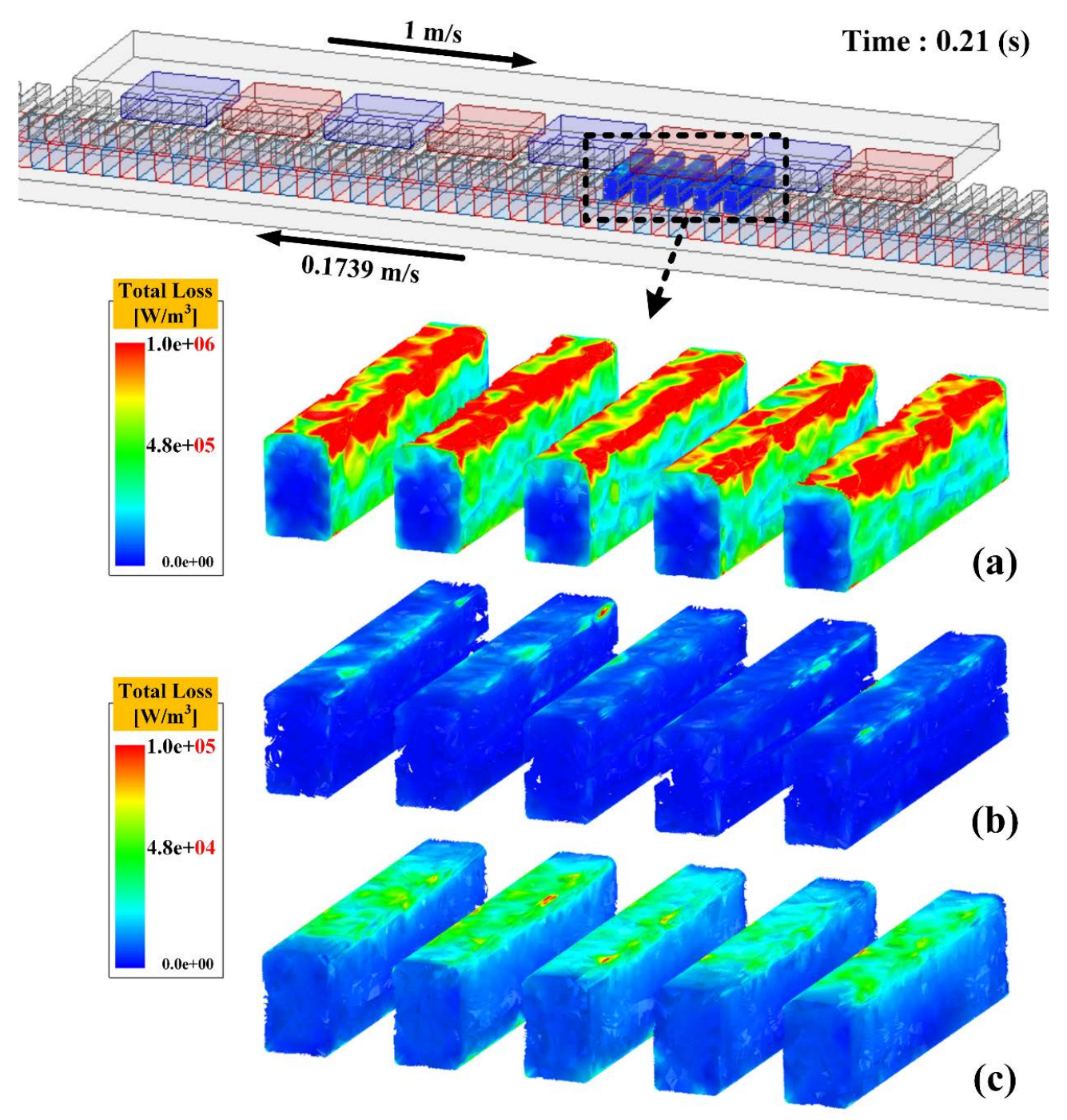

Fig. 5. Electromagnetic total loss distribution: (a) Iron, (b) 50PN470, and (c) SMC.

TABLE II. Comparison of Analysis Result and Stiffness Characteristics according to Material

| | Iron | 50PN470 | SMC |
|---|---|---|---|
| *Speed of LSM [m/s]* | 71.34 | 60.67 | 57.1 |
| *Force of HSM [N]* | 360.7 | 361.2 | 357.5 |
| *Force of LSM [N]* | 441.5 | 445.7 | 436.7 |
| *Pull-out Force [N]* | 6.3 | 4.5 | 3.7 |
| *Force Ripple of HSM [%]* | 3.7 | 3.66 | 3.8 |
| *Force Ripple of LSM [%]* | 7.28 | 6.42 | 6.39 |
| *Output Power [W]* | 54.96 | 54.1 | 50.42 |
| *Core Loss (Core) [W]* | - | 0.129 | 0.583 |
| *Eddy Current Loss [W]* | 16.5 | 6.44 | 6.2 |
| *Efficiency [%]* | 76.9 | 89.2 | 88.2 |
| *Young's modulus [GPa]* | 195 | 200 | 190 |
| *Possion's ratio* | 0.28 | 0.3 | 0.23 |
| *Tensile strength [MPa]* | 250 | 395 | 65 |
| *Yield strength [MPa]* | 250 | 275 | 65 |

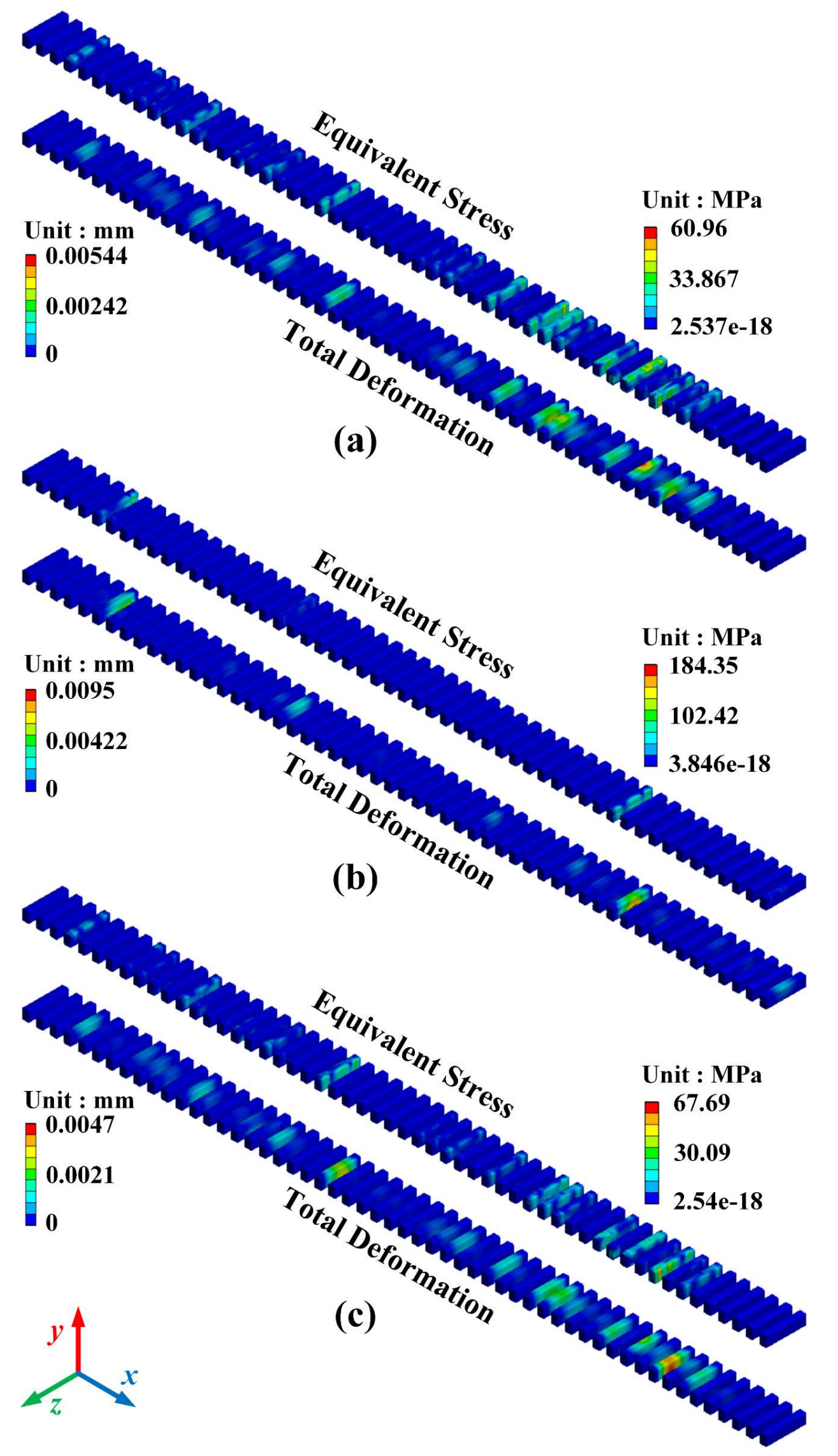

Fig. 6. Stress analysis of the flux-modulation pole: (a) Iron, (b) 50PN470, and (c) SMC.

- ✓ The total electromagnetic losses of the FMP are shown in Fig. 5.
- ✓ Fig. 6 shows the mechanical characteristic analysis results.
- ✓ Table II shows the results of the electromagnetic characteristics analysis results and the stiffness characteristics of the material of the FMP.

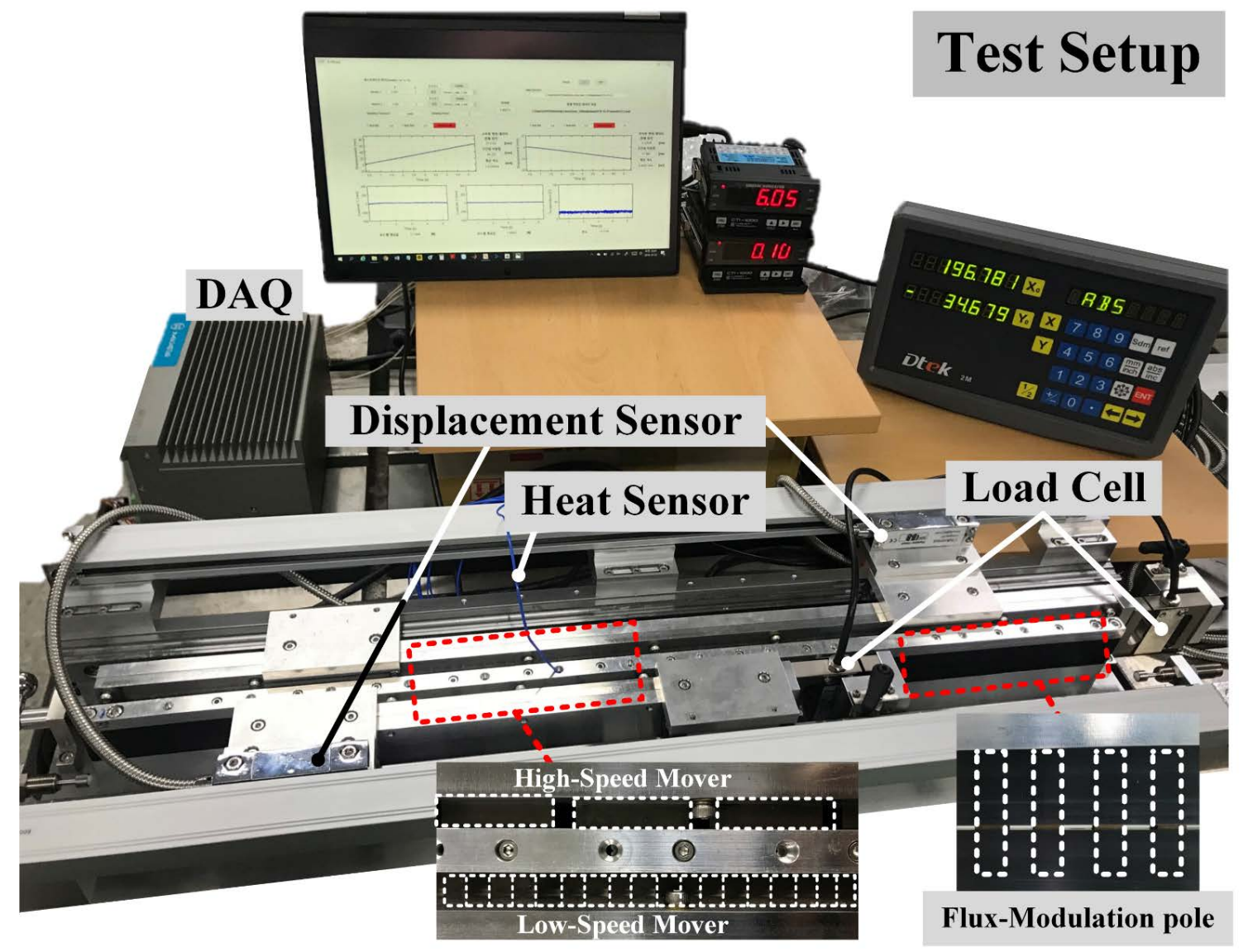

Fig. 7. Testing apparatus for measuring the magnetic torque and force of an actual manufactured gear.

- ✓ The electromagnetic losses can be known from the following Eq. (4) and (5).

$$P_e = \frac{l}{\sigma} \int J^2 dA \qquad (4)$$

$$P_{core} = P_h + P_e + P_a = k_h f_c B_c^{n_{st}} + k_e f_c^2 B_c^2 + k_a f_c^{1.5} B_c^{1.5} \qquad (5)$$

- ✓ where $P_e$, $l$ and  represent eddy current loss, core length and conductivity, and $J$ and $A$ represent current density and magnetic vector potential, respectively.
- ✓ where, $P_{core}$, $P_h$, $P_e$, and Pa are the core loss, hysteresis loss, eddy current loss, and excess loss. In addition, $k_h$, $k_e$, $k_a$, and $n_{st}$ are the hysteresis loss coefficient, eddy current loss coefficient, excess loss coefficient, and Steinmetz constant. And $f_c$ and $B_c$ are the frequency of the external magnetic field and flux density in the core, respectively.

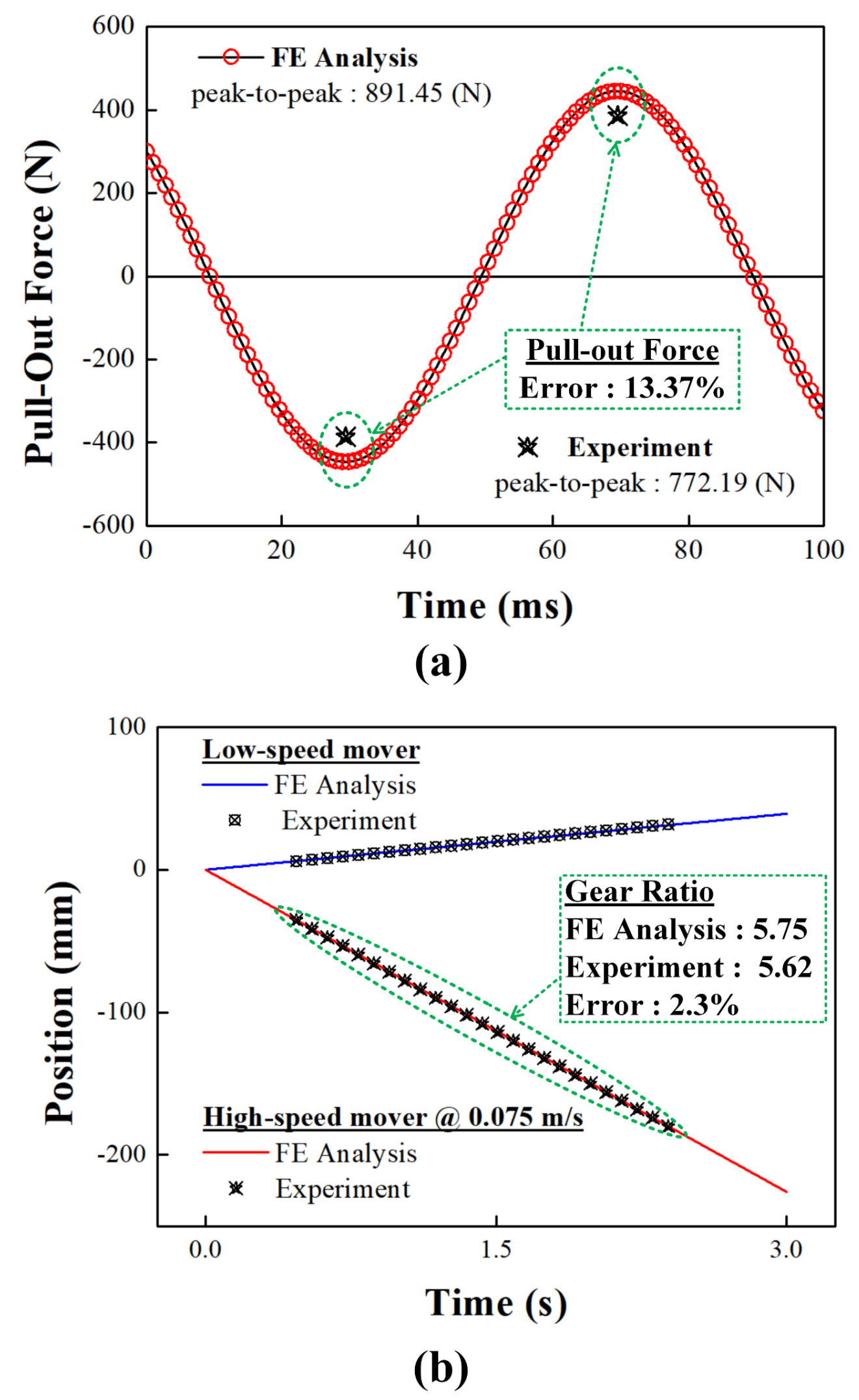

Fig. 8. Comparison of the experimental and FEA results: (a) pull-out force , (b) position

- ✓ The HSM rated speed was 1 m/s, but it was driven at 0.075 m/s for the convenience of analysis.
- ✓ Therefore, the comparison results are shown in Fig. 8; the analysis and experimental results are in good agreement with each other. The experimental results show a 2.3% error, which can be attributed to mechanical losses.

## IV. CONCLUSION

- ✓ MGs are power transmission devices for which it is important to analyze both the mechanical and electromagnetic characteristics. Therefore, in this study, the characteristics of LMGs with FMP materials of iron, electrical steel, and SMC were analyzed in order to develop an efficient and practical LMG model. Such a model was proposed in consideration of the electromagnetic and mechanical characteristics and subsequently fabricated and compared with the experimental results. This paper can serve as a reference for the optimal design of linear PM machines and LMGs.

Presented at the 26th International Conference on Magnet Technology , 22-27, September – Vancouver, Canada ; Tracking ID: Mon-Mo-Po1.09-09