A study on the design of propulsion/levitation/guidance integrated DSLIM with non-symmetric structure

Cite as: AIP Advances 10, 025031 (2020); https://doi.org/10.1063/1.5130416
Submitted: 16 October 2019 . Accepted: 23 January 2020 . Published Online: 20 February 2020

Kyo-Young Seo, Chan-Bae Park, Geochul Jeong, Jae-Bum Lee, Taehyung Kim, and Hyung-Woo Lee
A study on the design of propulsion/levitation/guidance integrated DSLIM with non-symmetric structure

Kyo-Young Seo, Chan-Bae Park, Geochul Jeong, Jae-Bum Lee, Taehyung Kim, and Hyung-Woo Lee

ABSTRACT

Research on the magnetic levitation driving system of Hyperloop which has emerged as the next new vehicle is being carried out. Recently, magnetic levitation driving systems use EMS (Electro-Magnetic Suspension) and EDS (Electro-Dynamic Suspension) methods, and both EMS and EDS methods use two or more systems for propulsion/levitation/guidance. However, using two or more driving systems cause complexity of structure of whole system and increase significantly maintenance costs. Therefore, to solve these problems, this study proposed the concept and structure of Double-Sided Linear Induction Motor (DSLIM) that can be generating propulsion/levitation/guidance in one system, and carried out basic design and performance analysis by analyzing the design requirements of DSLIM. In addition, a detailed design through the selection of design parameters and analysis of characteristics that significantly affect the output characteristics was carried out to derive a performance improvement model for DSLIM.

© 2020 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5130416

I. INTRODUCTION

Several studies are being conducted on the magnetic levitation driving system of Hyperloop that emerged as the next new vehicle. Hyperloop has emerged as a new form of transportation that solving the problem of limited speed and relatively expensive transportation costs of high-speed trains. Starting with the initial air injection and absorption formula, the driving system of the Hyperloop has been carried out research and development to the level where the vehicle drives at a speed close to the speed of sound inside the tube under atmospheric conditions close to vacuum using magnetic levitation. Several studies have been conducted on magnetic levitation driving systems, and China, Japan and Germany, which currently have leading technologies for magnetic levitation driving systems, use EMS (Electro-Magnetic Suspension) and EDS (Electro-Dynamic Suspension) methods. The EMS method performs propulsion and levitation functions in one device, uses a separate device for guidance, and the EDS method performs levitation and guidance functions in one device, and uses a separate device for propulsion. However, since EMS and EDS-type driving systems use more than one driving system for propulsion/levitation/guidance, which is the core technology of magnetic levitation trains, the problem arises: they complicate the structure of the whole system and increase significantly maintenance costs. To solve these problems, this study proposed the concept and structure of a Double-Sided Linear Induction Motor (DSLIM) that can carry out both propulsion, levitation, and guidance functions in a single system. In addition, a basic design and performance analysis were performed through the analysis of
the DSLIM design specifications, and the performance improvement model of double-sided linear induction motors, which can perform both propulsion, levitation, and guidance functions in one system was derived through the analysis of the characteristics of each parameter by selecting design parameters that greatly affect the output characteristics.6

II. STRUCTURE AND OPERATING MECHANISM OF DSLIM WITH NON-SYMMETRIC STRUCTURES

Fig. 1 is the application method of Double-Sided Linear Induction Motor (DSLIM) for applying high-speed tube train. A pair of primary sides with three-phase windings attached to each side of the secondary conductor attached to the underside of the vehicle are installed symmetrically along the track. The driving of DSLIM is driven by the Lorenz force induced on the secondary, using the secondary structure of the DSLIM and the symmetrical primary structure of the DSLIM, which, unlike typical LIM. The thrust force generated on the same principle as the propulsion principle of a typical LIM. The levitation force is caused by the transverse effects of the LIM and is affected by the alignment of the primary and secondary of the DSLIM. The guidance force is caused by the vertical force characteristic of the LIM and use repulsive magnetic field that generated at high speed. As a result, the propulsion/levitation/guidance force of the DSLIM generated in one system at the same time.

III. BASIC DESIGN AND ELECTROMAGNETIC CHARACTERISTICS ANALYSIS OF DSLIM

A. Basic design of DSLIM

Using the know-how of LIM and the symmetry of DSLIM, the basic model design for 1 module of DSLIM was performed and the design specifications were illustrated in Table I. When looking at the main design specifications, the values of efficiency and power rates were low, because DSLIM has a very large leakage of magnetic flux compared to single-sided LIM because structure of primary is non-symmetry and has a double air gap. The winding method is 2 layer distributed short type to reduce the leakage reactance of winding and harmonics, and improve the waveform. Mechanical air gap is selected 20mm on both sides, with the center of the secondary reaction plate. This is to prevent collisions between the secondary and primary and to ensure smooth curve driving. The pole pitch was

| Specification          | Value       | Specification          | Value       |
|------------------------|-------------|------------------------|-------------|
| Power                  | 15.3 [MW]   | Winding method         | 2 layer distributed short |
| Rated speed            | 1000 [km/h] | Short-pitch-factor     | 5/6         |
| Number of pole         | 2           | Stack                  | 288 [mm]    |
| Thrust force           | 55 [kN]     | Airgap                 | 20 [mm]     |
| Efficiency             | 0.7         | Current density        | 4           |
| Power factor           | 0.3         | Number of slot per pole| 2           |
| Levitation force       | 110 [kN]    | Core material          | 35PN230 (S08) |
| Current                | 7 [kA]      | Secondary thickness    | 20 [mm]     |
| Rated slip             | 0.2 [s]     | Secondary material     | Aluminum    |
| Rated frequency        | 386 [Hz]    | Wedge depth            | 4 [mm]      |
| Teeth width            | 50 [mm]     | Slot depth             | 125 [mm]    |
| Yoke                   | 60 [mm]     | Slot width             | 100 [mm]    |
chosen as 450mm, taking into account the large air gap and manufacture of DSLIM. The material of the primary core is selected as 35PN230 and used in laminating. The secondary material was selected with aluminum. The current density was chosen as 4A/mm² because it uses a natural cooling method. Secondary reaction plate has a thickness of 30mm and the air gap is 20mm on the single-sided. The laminating length of the primary is 288mm, the slot depth is 125mm, the slot width is 100mm, the teeth width is 50mm, the yoke is 60mm and the wedge is 4mm.

B. Electromagnetic characteristics analysis of basic design model

For accurate analysis of propulsion/levitation/guidance forces, the 2D FEA which considers the generated eddy current only in one-dimension is not suitable, and the 3D FEA which takes into account the eddy current in two-dimensions must be used. Therefore, 3D FEA models of DSLIM were designed using electromagnetic character analysis tools, as shown in (a) of Fig 2, and electromagnetic characteristics analysis of propulsion and levitation forces were performed and presented in (b) of Fig. 2. Looking at the analysis results, it can be found that the maximum propulsion generating slip is 0.5s, which is higher than the target rated slip, and that the target performance is not satisfied with the rated slip with a thrust force of 23.83kN and a levitation force of 2.83kN. Therefore, in order to achieve the target performance, detailed design is required through the selection of the design parameters of the primary and secondary that affect the output characteristics, and the analysis of the electromagnetic characteristics. However, 3D FEA have problems that require excessive analysis time. Therefore, 2D FEA with relatively...
less analysis time compared to the 3D FEA should be performed, and the ratio of the generation of levitation force to thrust force was calculated as in (c) of Fig. 2. If this is used, a 2D FEA that can measure only the thrust force can be performed to estimate the levitation force.

IV. DETAILED DESIGN AND ELECTROMAGNETIC CHARACTERISTICS OF DSLIM

A. Detailed design of DSLIM

Through the analysis of characteristics of the basic design model of DSLIM 1 module in Section III B, detailed design through analysis of design parameters of primary and secondary of DSLIM is required to achieve the target performance. Prior to detailed design, finite element analysis techniques of DSLIM for efficient parameter analysis were reviewed. When analysis electromagnetic characteristics through finite element method, the induction motor takes an excessive amount of time to reach steady area. In addition, the characteristics of each slip, which is the difference between the relative speed of the primary and secondary and the speed of magnetic field, are different. In particular, high-speed motors, such as DSLIM, have very high operating frequencies, so the analytical step should be carefully divided. The analysis time is longer because of the long transient before the waveform of the analysis converges into its normal state. In addition, unlike 2D FEA, 3D FEA takes into account all three-axis directions, resulting in a more than 100 times increase in the number of mesh. Therefore, 3D FEA is not appropriate because parameter analyses for detailed design have many number of analyses depending on the number of parameter variables.

However, because 3D FEA is essential for accurate performance analysis of DSLIM, in this paper, the ratio of levitation force to thrust force is calculated as shown in (c) of Fig. 2, using 3D FEA, and this can be used to estimate the levitation force by multiplying the ratio after measuring the thrust force through 2D FEA. Thus, parameter analyses for detailed design were performed with 2D FEA. In addition, if the symmetry of DSLIM is used, it is possible to analyze the half model rather than the full model. Therefore, the half model was used to reduce the analysis time as shown in Fig. 3.

Table II is the design parameters and ranges for the detailed design of the DSLIM. Design parameters were calculated by considering the characteristics of DSLIM with very large air gap and double-sided structure of primary. For the efficiency of the analysis, the materials of the secondary conductor were selected as Stainless-Steel with a conductivity of about 3% compared to the Aluminum, with different conditions identical in the basic design specification. This is because the high conductivity of the Aluminum material creates a strong repulsive magnetic field at high speed, thus impeding the performance of the DSLIM. Short-Pitch-Factor were randomly chosen using empirical design techniques.

B. Electromagnetic characteristics analysis of detailed design model

The propulsion sensitivity analysis for the selected parameters was performed as shown in Fig. 4. In the case of number of slot per pole 2, the sensitivity analysis of the thickness and propulsion of the air and secondary conductor plates was performed as in Fig. 4 (a) without analyzing the entire slip area taking into account the efficiency of the analysis because the number of parameter variables is too many number of analyses depending on the number of parameter variables.

However, because 3D FEA is essential for accurate performance analysis of DSLIM, in this paper, the ratio of levitation force to thrust force is calculated as shown in (c) of Fig. 2, using 3D FEA, and this can be used to estimate the levitation force by multiplying the ratio after measuring the thrust force through 2D FEA. Thus, parameter analyses for detailed design were performed with 2D FEA. In addition, if the symmetry of DSLIM is used, it is possible to analyze the half model rather than the full model. Therefore, the half model was used to reduce the analysis time as shown in Fig. 3.

Table II is the design parameters and ranges for the detailed design of the DSLIM. Design parameters were calculated by considering the characteristics of DSLIM with very large air gap and double-sided structure of primary. For the efficiency of the analysis, the materials of the secondary conductor were selected as Stainless-Steel with a conductivity of about 3% compared to the Aluminum, with different conditions identical in the basic design specification. This is because the high conductivity of

| Parameter       | Value          | Parameter       | Value          |
|-----------------|----------------|-----------------|----------------|
| Airgap          | 10 ~ 25 [mm]   | Number of slot  | 2, 3, 4        |
|                 | (5mm step)     | per pole       |                |
| Secondary       | 10 ~ 30 [mm]   | Short pitch     | 5/6, 6/9~8/9,  |
| thickness       | (10mm step)    | factor          | 9/12~11/12 (1 step) |

Table II. Range and design parameters of DSLIM.

FIG. 3. 2D FEA model of DSLIM.
(d) is the result of a performance comparison between the best models among the results of (a), (b), (c), and the final parameters of the DSLIM performance improvement model are selected and summarized in Table III. However, the thrust force of the selected model is 249.85kN, which is about 4.5 times the required thrust force of 55kN.

However, considering that the ratio of the levitation force to propulsion force at 0.2s, the rated slip at (c) of Fig 2, is about 12%,
TABLE III. Final Specification of detailed design model of DSLIM.

| Parameter                  | Reference spec. | → final spec. |
|----------------------------|-----------------|---------------|
| Airgap                     | 20mm            | → 10mm        |
| Secondary thickness        | 20mm            | → 10mm        |
| Thrust force               | 55kN            | → 249.85kN    |
| Levitation force           | 2.83kN          | → 24.985kN    |
| Input current              | 7kA             | → 3.5kA       |
| Maximum thrust force slip  | 0.2s            | → 0.08s       |
| Number of slot per pole    | 2               | → 4           |
| Short-pitch-Factor         | 5/6             | → 10/12       |

Further studies are needed to improve the levitation force because the required levitation force is not satisfied.

In addition, field strength in the rated slip was analyzed as shown in Fig. 5. Looking at the analysis results, the value of the Magnetic Flux Density in airgap at rated slip is 0.4266T. When analyzing Magnetic Flux Density in airgap, there is no saturation of the teeth and yoke section based on 1.8T.

V. CONCLUSION

This paper is a research on the design of propulsion/levitation/guidance integrated Double-Sided Linear Induction Motor (DSLIM) for the application of Hyperloop. To solve the conventional problem of Hyperloop driving systems, the concept and structure of DSLIM with non-symmetric structure that can be carry out both propulsion/levitation/guidance functions in one system were proposed. In addition, by analyzing the design requirements of DSLIM, the basic design of DSLIM was carried out, and 3D FEA was carried out for measuring propulsion/levitation/guidance force. Basic design result analysis does not achieve target performance with 23.83kN thrust and 2.83kN levitation force in rated slip. To achieve the target performance, primary and secondary design parameters of DSLIM affecting the output characteristics were selected. Through a sensitivity analysis between design parameters and thrust forces, the performance improvement model of DSLIM was derived. Primary
and secondary design specifications of the final DSLIM performance improvement model are number of slots per pole 4, Short-Pitch Factor 10/12, secondary thickness 10mm, airgap 10mm, and the thrust force is approximately 4.5 times greater than the target thrust force of 55kN. However, considering the ratio of levitation force to thrust force, additional studies are needed to improve levitation force because the required levitation force is not satisfied. In future studies, theory of 3D FEA will be established to reduce the analysis time to perform levitation and guidance analysis of the performance improvement model. In addition, performance testing is essential to verify the feasibility of DSLIM, and a small-scaled rotary type tester will be produced considering limited test conditions (space and cost) and safety.

ACKNOWLEDGMENTS

This work is supported by the Korea Agency for Infrastructure Technology Advancement(KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 19CTAP-C1452921-02).

REFERENCES

1. H. W. Lee, K. C. Kim, and J. Lee, "Review of maglev train technologies," IEEE Trans. Magn. 42(7), 1917–1925 (2006).
2. H. W. Cho, J. S. Bang, H. S. Han et al., "Status of advanced technologies and domestic researches for development of Korean next generation maglev," The transaction of the Korean Institute of Electrical Engineers 57(10), 1767–1776 (2008).
3. H. W. Cho, C. H. Kim, H. S. Han et al., "Design and characteristic analysis of hybrid-type levitation and propulsion device for high-speed maglev vehicle," The transaction of the Korean Institute of Electrical Engineers 59(4), 715–721 (2010).
4. L. Yungang, C. Wensen, Z. Xiao et al., "Structure calculation of permanent-magnet EDS maglev train and its application," Electric Drive for Locomotives 5(6), 29–32 (2005).
5. Y. Yan, Y. Li, and C. Hu, "Analysis of levitation stability and technology characters of EDS and EMS hybrid maglev," Proceedings of CSEE 27(6), 53–56 (2007).
6. H. S. Seol, S. D. Lee, and J. Lee, "Optimal design and analysis of induction motor for propulsion of electric railway," Journal of the Korean Society for Railway 19(5), 600–608 (2016).