A Study on the Structure of Linear Synchronous Motor for 600 km/h Very High Speed Train

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Abstract: Recently, an interest in a hybrid system combining only the merits of the conventional wheel-rail system and Maglev propulsion system is growing as an alternative to high-speed maglev train. This hybrid-type system is based on wheel-rail method, but it enables to overcome the speed limitation by adhesion because it is operated through a non-contact method using a linear motor as a propulsion system and reduce the overall construction costs by its compatibility with the conventional railway systems. Therefore, a comparative analysis on electromagnetic characteristics according to the structural combinations on the stator-mover of LSM (linear synchronous motor) for VHST (very high speed train) maintaining the conventional wheel-rail method is conducted, and the structure of coreless superconducting LSM suitable for 600 km/h VHST is finally proposed in this paper.

Key words: Very high speed train, linear synchronous motor, coreless, superconductivity, wheel-rail.

1. Introduction

The pace of globalization is increasing, and consequently, the need for a high-speed transportation system is also increasing. Speed is one of the most important factors of the competitive edge of any means of transportation. Speed is particularly more important in Northeast Asia, which is positioned to become the economic center of the world in the near future [1-3]. Fig. 1 shows the top five records of high speed train in the world [1]. As shown in Fig. 1, the fastest ground transportation system developed until now is Japan’s maglev train (581 km/h). The research and development of Maglev train began in 1960’s and Germany and Japan’s technology is at the stage of practical application by establishing the test lines. Germany’s transrapid were constructed in Shanghai, China, in 2003 as 430 km/h commercial routes which is the world’s only commercial system. Japan’s maglev train can be operated at the maximum speed of about 581 km/h, but its commercialization is increasingly difficult due to its the incompatibility with the existing railways as well as high construction and maintenance costs [4, 5].

Recently, an interest in a hybrid system combining only the merits of the conventional wheel-rail system and maglev propulsion system is growing as an alternative to high-speed maglev train. This hybrid-type system is based on wheel-rail method, but it enables to overcome the speed limitation by adhesion because it is operated by a non-contact method using a linear motor as a propulsion system and reduce the overall construction costs by its compatibility with the conventional railway systems [6-8]. Therefore, a comparative analysis on electromagnetic characteristics according to the structural combinations on the stator-mover of LSM (linear synchronous motor) for VHST (very high speed train) maintaining the conventional wheel-rail method is conducted, and the structure of coreless superconducting LSM suitable for 600 km/h VHST is finally proposed in this paper.
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2. Basic Design of LSM for 600 km/h VHST

2.1 Structure Deductions of LSM for 600 km/h VHST

In this paper, a basic concept for 600 km/h VHST is as follows: A propulsion system is LSM and a guide way system is a wheel-rail method. In case of LSM for propulsion, the 3-phase armature is installed on the ground between the rails and the field electromagnet is installed on the lower of vehicles. Fig. 2 shows a concept of the structure of LSM for 600 km/h VHST.

Some structure which can be applied to the LSM for 600 km/h VHST is firstly derived. Fig. 3 shows a definition on various structures of LSM for 600 km/h VHST. As shown in Fig. 3, the structure of the 3-phase armature which is installed on the ground between the rails is possible to be a core type and a coreless type. In addition, the structure of the field electromagnet which is installed on the lower of vehicles is possible to be an electromagnet with core and a superconducting electromagnet without core. Therefore, four models are selected as the candidate structure and the basic design is performed in this paper. Table 1 shows candidate structures of LSM model for 600 km/h VHST.

2.2 Basic Design of LSM for 600 km/h VHST

The basic design of LSM for 600 km/h VHST is performed and the common design specifications of each LSM models are summarized in Table 2. Rated capacity, rated thrust, airgap and pole pitch of stator are 26 MW, 276 kN, 10 mm and 258 mm, respectively.

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Fig. 1  Top five records of high speed train in the world.

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**Table 1  Candidate structures of LSM model for 600 km/h VHST.**

| Model   | Armature    | Field magnet   |
|---------|-------------|----------------|
| 1(CA-CM)| Core type   | Core type EM   |
| 2(CLA-CM)| Coreless type | Core type EM    |
| 3(CA-CLSM)| Core type | Coreless type SM |
| 4(CLA-CLSM)| Coreless type | Coreless type SM |

The core type armature/core type electromagnet (CA-CM) LSM model is firstly designed and the other three models are implemented by changing the properties of the materials by the analytical method.

Fig. 4 shows a basic designed 2-dimensional analytical model of CA-CM LSM.
Table 2: Common design specifications of each LSM model.

| Content                        | Value       |
|--------------------------------|-------------|
| Rated capacity of total LSM    | 26 (MW)     |
| Thrust force (300/600 km/h)    | 276/152 (kN)|
| Frequency (300/600 km/h)       | 161.5/323 (Hz)|
| Input phase voltage (300/600 km/h) | 4,857/5832 (V) |
| Input current of armature (300/600 km/h) | 1,583/823 (A) |
| Airgap/pole pitch              | 10/258 (mm) |
| Armature pole number           | 200 (EA)    |
| Armature series turns          | 200 (Turns) |

3. Electromagnetic Characteristic Analysis of Each LSM

3.1 Analysis Conditions of LSM Models

The electromagnetic characteristic analysis of each LSM design model (CA-CM, CLA-CM, CA-CLSM, CLA-CLSM) is performed using 2-D FEM analysis tool. The analysis procedure is as in the following. First, the basic characteristics of the CA-CM typed LSM are conducted. In the analysis of the other 3 LSM models, the 3-phase current source of the ground armature remains the same based on the thrust 2.6 kN which is generated during 600 km/h operation of the CA-CM typed LSM with 11 poles per module. Then, the necessary MMF (magnetomotive force) of the on-board field magnet is derived and the thrust and normal force are calculated.

3.2 Analysis Results of LSM Models for 600 km/h VHST

Fig. 5 shows an airgap flux density distribution between the ground armature and the on-board field magnet of each LSM (600 km/h). As shown in Fig. 5, the airgap flux density (RMS value: 0.67 T) of the CLA-CLSM type LSM is the largest.

Fig. 6 shows the magnetic flux density distributions of each LSM model (600 km/h). As shown in Fig. 6, there is a problem that the magnetic flux saturation occurs when the field magnet is a core type because the large MMF is required on the field magnet when the ground armature is a coreless type. Therefore, it is appropriate to select the field magnet of coreless type when the ground armature is coreless type. Fig. 7 shows the thrust and normal force properties of each LSM model (600 km/h). As shown in Fig. 7, as a result of examining the thrust and normal force characteristics according to the phase angle variation of the three-phase current applied to the ground armature, the variation trend of the thrust force for each model is similar, but the variation trend of the normal force is different. In case of normal force, it is expected that the large normal force is able to be obtained if the ground armature and the on-board field magnet are a core type or the filed magnet is a superconducting magnet with coreless type. Table 3 shows the analysis results of electromagnetic characteristics on each LSM model. As shown in Table 3 the thrust ripple of CLA-CM model is the smallest, but the CLA-CM model has a problem which the field magnet is saturated. The CLA-CLSM model has an appropriate level in all performance indicators.

In conclusion, it is considered that the coreless type is suitable for the ground armature and the coreless superconducting magnet type is suitable for the field magnet because the performance, weight and cost of the LSM system for propulsion on the 600 km/h VHST should be considered at the same time. In the future, it will be proceeded an optimum design of the LSM.
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Fig. 6  Magnetic flux density distributions of each LSM model (600 km/h).

Fig. 7  Thrust and normal force properties of each LSM model (600 km/h).

4. Conclusions

A comparative analysis on electromagnetic characteristics according to the various structural combinations on the stator-mover of LSM for 600 km/h VHST maintaining the conventional wheel-rail method is conducted and some results are summarized in this paper. Four LSM models are selected as the candidate structures for the LSM and each design is performed. The thrust ripple of CLA-CM model is the smallest, but the CLA-CM model has a problem which the field magnet is saturated. The CLA-CLSM model has an appropriate level in all performance indicators. In conclusion, it is considered that the coreless type is suitable for the ground armature and the coreless superconducting magnet type is suitable for the field magnet because the performance, weight and cost of the LSM system for propulsion on the 600 km/h VHST should be considered at the same time.
Table 3  Analysis results of electromagnetic characteristics on each LSM model.

| Contents  | Magneto-motive force (kATurns) | Airgap flux density (T) | Thrust force (kN) | Thrust force ripple (kN) | Normal force (kN) | Saturation on the cores | on Construction cost |
|-----------|-------------------------------|-------------------------|-------------------|------------------------|------------------|------------------------|---------------------|
| CA-CM     | 5.2                           | 0.45                    | 2.6               | 1.97                   | 41.5             | X                      | High                |
| CLA-CM    | 59.8                          | 0.56                    | 2.6               | 0.47                   | -0.28            | O                      | Very low            |
| CA-CLSM   | 80.6                          | 0.45                    | 2.6               | 3.85                   | 52.4             | X                      | Very high           |
| CLA-CLSM  | 197.6                         | 0.67                    | 2.6               | 1.95                   | 32.2             | X                      | Low                 |

the future, it will be proceeded an optimum design of the LSM based on the combination of the coreless ground armature and on-board superconducting electromagnet for the 600 km/h VHST.

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