Proposal of Contactless Vertical Transportation System which can also move in Horizontal Direction

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Abstract

We propose a new contactless vertical transportation system, which has coreless linear synchronous motor (LSM) with Halbach magnet array for hoisting at each side and four electromagnets with permanent magnet for posture control. These electromagnets work also field magnets of LSM for horizontal movement. This system can be able to achieve 5-degrees-of-freedom active posture control. In this paper, first, characteristics of linear Halbach magnet array used for hoisting LSM are analyzed. Then posture controlling method is examined by simulation.

1. Introduction

For effective space use in cities, it is one of the most important task to realize high performance of vertical transportation system. However, conventional elevator using wire can drive only one cage in one shaft. So, elevators occupy large space in buildings and it has become principal obstacle for efficient use of space. To solve this problem, "Ropeless elevator" is proposed and quantitatively estimated its performance required for. Consequently, to realize efficient transportation, it doesn't necessarily need fast operating speed, but horizontal movement for turning back must be operated at high speed. In the meantime, from technical point of view, long stator type linear motor is recommended. In 1996, as a part of research for effective utilization of underground space, Engineering Advancement Association of Japan (ENAA) produced a test model. But its structure was very complex, including its shunting system which is operated by route switching. And there is another method which has realized contactless operating by using normal force of linear motor, but it doesn't considered about shunting.

In this paper, contactless vertical transportation system which can also move in horizontal direction is proposed. In this system, hoisting LSM using Halbach magnet array and U-shaped electromagnet for posture control are installed. Then, characteristics of hoisting motor are analyzed, and posture control method is examined.

2. Proposed vertical transportation system

2.1 Components of proposed system

Structure of proposed system is shown in Fig.1.Hoisting linear synchronous motors (LSM) are built in 2 opposing sides of the cage. Hoisting LSM is long stator type and Halbach magnet array which generates large magnetic field in only one side is used. So, armature windings can generate sufficient hoisting power without core. This enables suppression of the ripple of torque and reduction of electric power supplying to cage. Additionally, by installing iron plate on the back of armature windings, force of restitution in *y*-direction and yawing direction can be realized. Also, U-shaped electromagnets (permanent magnets are used in combination) for posture control are installed on 4 of the 8 vertex of the cage. These magnets also work as field magnets in LSM for horizontal movement (using iron core in armature windings).

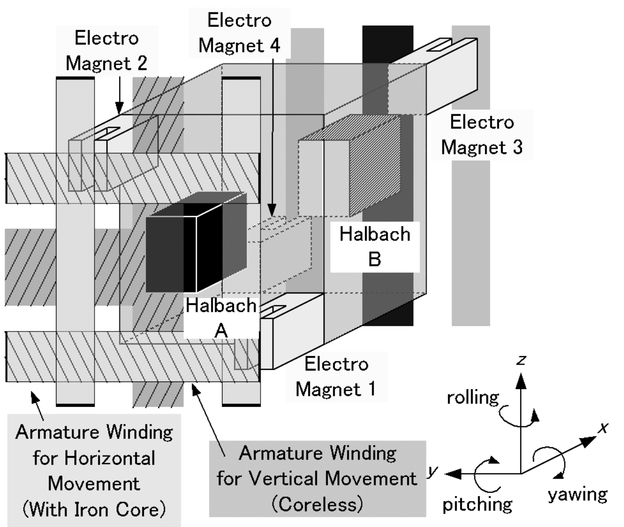

Fig. 1 Structure of Proposed Vertical Transport System

2.2 Structure of shunting place

In the shunting place of vertical and horizontal shafts shown as fig.2, iron cores opposing to U-shaped electromagnets and armature windings of hoisting LSM overlap. So, iron plates opposing to U-shaped electromagnets and ones installed on the back of armature windings are corresponded in their surface positions. And armature windings used in LSM stick out inside of the shaft and U-shaped electromagnets built on the surface of cage stick out to the wall of the shaft. This structure realizes posture controlling in the shunting place. However, in the shunting place, space where hoisting armature windings cannot install exists. So the permanent magnet used for field magnets of hoisting LSM must have ability to hoist cage in such spaces.

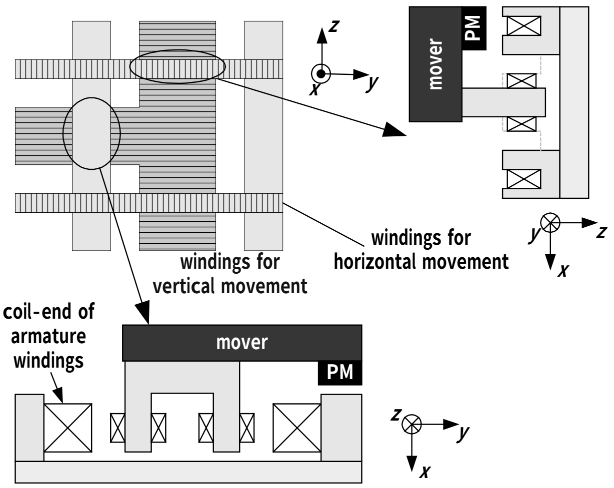

Fig. 2 Structure at Shunting Place

3. Hoisting coreless LSM

3.1 Magnetic field generated by Halbach magnet array

Hoisting LSM is required sufficient performance to support the weight of cage itself. In this system, Halbach magnet array is adopted in field magnets of hoisting LSM, and the armature of hoisting LSM is coreless.

Halbach magnet array, or the array direction of magnetization of magnets is gradually changing, can generate large sinusoidal magnetic field on one side and small one on the other side, and this characteristic increases when magnets are divided into smaller pieces.

Magnetic field generated by Halbach magnet array when applied to field magnets of hoisting LSM is calculated by 2-dimensional analysis. Relation between displacement from the surface of magnet and magnetic flux density at the center of magnetic pole is shown in fig.3, where thickness of magnet is 20[mm], pole pitch is 40[mm], remanent flux density B_r=1.24[T], coercive force H_c=9×10^5[A/m]. This analysis shows that when magnet is divided into smaller pieces, the magnetic flux density becomes larger. But also shown is that such effect weakens when displacement of magnets from armature windings increases. So, in the following argument, number of pieces of magnet is determined as 4.

Then, magnetic flux density at various values of pole pitch and thickness of magnet is shown in fig.4. This figure shows that the range where sufficient magnetic flux exists depends on the value of pole pitch. And also shown is that thickness of magnet influences little when the value of thickness exceeds some extent.

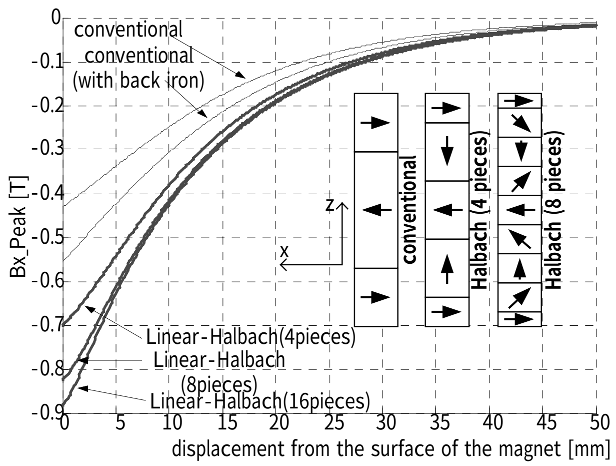

Fig. 3 Influence of the number of pieces to Magnetic Flux

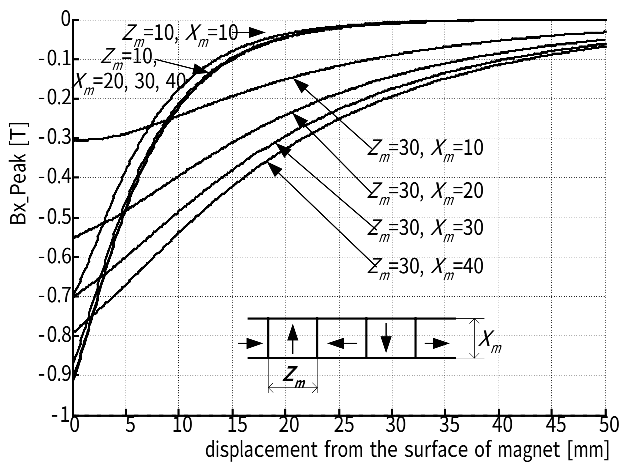

Fig. 4 Influence of the magnet size to Magnetic Flux

3.2 Attractive force between iron plates and permanent magnet

Generally, coreless armature windings don't generate attractive force which is regarded as a large problem in linear motors conventionally. However, proposed system doesn't have a possible method for controlling the force in x and yawing directions. So, we consider about posture controlling in these directions by giving adequate attractive force to hoisting LSM.

Relations between hoisting or attractive force and depth of slot are shown in fig.5. This figure indicates that hoisting force depends little on depth of slot, but attractive force largely depends on it. Thus, we can obtain intended attractive force by adjusting the position of iron plates.

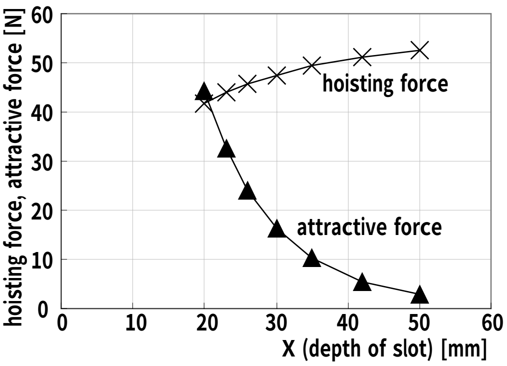

Fig. 5 Hoisting Force and Attractive Force of the LSM

4. Posture controlling method

4.1 Posture controlling method applied to proposed system

In the system shown in fig.1, 2 hoisting LSM control the posture of z direction, and 4 U-shaped electromagnets operate 3-degree-of-freedom posture control, in x direction, pitching direction and rolling direction. And iron plates are installed on the back of hoisting armature. Attraction force between iron plates and permanent magnets on the cage are used for restitution in y direction and rolling direction. Although, there is a possibility of controlling force in y direction by controlling U-shaped electromagnet or d-axis current of hoisting LSM, this paper deals with 3-degree-of-freedom posture control, in x direction, pitching direction and rolling direction.

4.2 3-degree-of-freedom posture control by using U-shaped electromagnets

Posture control needs coordinated control of 4 U-shaped electromagnets because they cannot generate repulsive force. In vertical transportation system proposed, relation between the force generated by electromagnets and controlling force in respective degree-of-freedom is as below.

$$\begin{aligned} F_x &= -F_1 - F_2 + F_3 + F_4 \\ T_p / L_z &= +F_1 - F_2 + F_3 - F_4 \\ T_r / L_y &= -F_1 + F_2 + F_3 - F_4 \end{aligned} \qquad (1)$$

F_1, F_2, F_3, F_4 : Force generated by 4 U-shaped electromagnet respectively.
F_x : Controlling power in x direction
T_p, T_r : Controlling torque in pitching or rolling direction
L_y, L_z : Displacement of electromagnets in x or y direction from center of gravity of cage

And, allocating attractive forces are represented by equations below.

$$\begin{aligned} F_1 &= 0.5F_{\max} - F_x/4 + T_p/4L_z - T_r/4L_y \\ F_2 &= 0.5F_{\max} - F_x/4 - T_p/4L_z + T_r/4L_y \\ F_3 &= 0.5F_{\max} + F_x/4 + T_p/4L_z + T_r/4L_y \\ F_4 &= 0.5F_{\max} + F_x/4 - T_p/4L_z - T_r/4L_y \end{aligned} \qquad (2)$$

$F_{\max}$: Maximum attractive force of actuator

Thus, 3-degree-of-freedom control is operated. Additionally, by using electromagnet and permanent magnet in combination in order that U-shaped magnet generate attractive force $0.5F_{\max}$ with zero controlling current, consumption of electric power can be reduced greatly.

4.3 Structure and characteristic of U-shaped electromagnet

Structure of U-shaped electromagnet is shown in fig.6. By setting permanent magnet in center, volume of U-shaped electromagnet becomes bit larger. But this structure enables high tolerance of field weakening of permanent magnet.

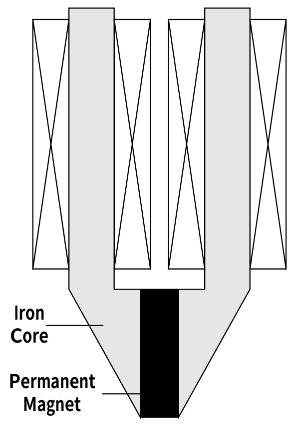

Fig. 6 U-shaped Electromagnet for Levitation Control

By calculating characteristic of attractive force of this electromagnet using 2-dimensional finite element method, attractive force of electromagnet when opposing to iron plate is represented as below.

$$F = \frac{3.88(i + 4.96)^2 + 2.75}{(g + g_M)^{1.94}} 10^{-5} \qquad (3)$$

g : Gap length
g_M : Converted value of the thickness of permanent magnet into gap length (0.0015m)

In the same way, attractive force when opposing to LSM for horizontal movement is represented as below.

$$F = \frac{7.06(i + 4.79)^2 + 6.07}{(g + g_M)^{1.79}} 10^{-5} \qquad (4)$$

By these equations, when U-shaped electromagnets are opposing to LSM with nominal gap length, the attractive force reduces by 20%.

5. Summary

In this paper, we dealt with the concept of completely contactless vertical transportation system which can also move in horizontal direction.

First, structure of this system is stated. Then, magnetic field generated by Halbach magnet array is analyzed. In consequence, adequate number of division, pole pitch, and thickness of magnets figured out. Then we proposed force allocation of 4 U-shaped electromagnet for the 3-degree-of-freedom posture controlling.

6. Future works

About posture control, passive stability is obtained in y direction, but the method of active control have not considered until now. However, considering hardware components of proposed system, freedom of controlling also exists in y direction. So, concrete method of controlling this direction must be examined in the future. Also about hoisting system, examinations are needed for controlling method in shunting place where armature windings abut against, and for method of position sensing. After solving these problems, we will demonstrate the methods proposed by producing test model.

References

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