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Analysis and measure of novel stereo-garage driven by linear induction motor

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Abstract: The car access time is a key parameter, especially in a huge stereo-garage, where this one should be decreased as much as possible. This paper proposes a novel stereo-garage. Adopting the linear induction motors (LIMs), the system has a simple structure and rapid response capability. In the stereo-garage, several LIMs are installed below the crossbeam on a lifting platform, and several LIMs are fixed on the top of a moving frame. During the operation of LIMs, the moving frame moves forward and backward to reach the required parking place, whereas the crossbeam moves horizontally in order to take or store the vehicle rapidly. All these LIMs are the same and should be designed at a low frequency. The influences of key structure parameters and dynamic performances are investigated, based on FEM. The predicted results are validated by a prototype. Finally, the designed LIMs are successfully applied in two 8-layer stereo-garages.

Key words: FEM, linear induction motors, low frequency, stereo-garage

1. Introduction

The stereo-garage is very important in the cities of modern society since there are more and more cars. The car access time is a key parameter, especially in huge stereo-garages. However, it is limited in traditional stereo garages due to the intermediate conversion devices, such as chains and gears [1-2]. In order to shorten the access time as much as possible, the use of linear motors (LMs) is strongly recommended. They can directly drive stereo-garage without any intermediate devices [3].

Among different structures of LMs, the linear induction motors (LIMs) are widely applied in transportation, logistics and industry due to the simpler construction and lower cost than others. Although LIMs have different structure types, such as single-side, double-side, tubular, disc, etc., the most popular is the single-side compound-secondary, which is applied in many devices.

Regarding LIMs, the thrust force and normal force under constant voltage excitation or constant current excitation are investigated by adopting the analytical electromagnetic field solution [4]-[7]. The biggest disadvantage is the calculation accuracy that is affected by many simplifications used for solving the complex mathematical operation. In order to improve the calculation accuracy and also consider the transverse edge effect, the finite element (FE) method is often adopted.

Due to the required low operating velocity at this application, the LIMs should be designed with a low rated frequency [8]-[9]. Moreover, the current should be decreased as much as possible to avoid magnetic field saturation and lower the capacity of an inverter. These cause that the LIMs of stereo garages differ from the normal LIMs. However, there are not many publications in this research field.

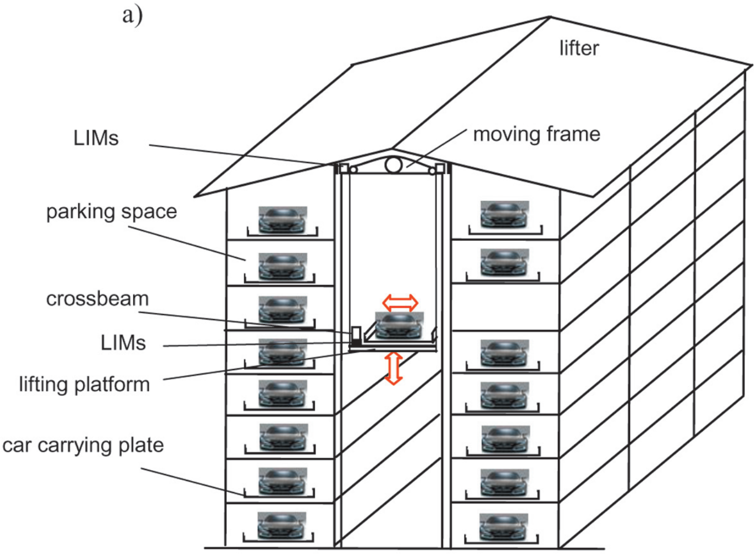
This paper mainly introduces the structure and operation principle of novel stereo garage driven by LIMs, to obtain the design specifications of LIM. Based on FEM, the influence of the structure parameter and dynamic performance are investigated. Finally, the predicted results are validated by the prototype measurement.

2. Structure of the novel stereo-garage

Figure 1(a) shows the diagram of one unit in the stereo garage driven by LIMs. Figure 1b) shows its vertical view. The unit number is an integer, such as 1, 2, 3 etc.

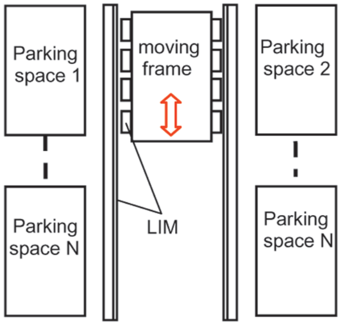
There are several LIMs in one unit. They are fixed on the moving platform and lifting frame respectively, which are located in the middle of the stereo garage. In each layer, the parking spaces can be 2, 4, 6, 8, 10 etc. As it can be seen, the LIMs are mounted on the top of the moving frame, which is a longitudinal moving mechanism. On each side, four primaries in parallel are fixed in the moving frame, and they use the same long secondary in the bracket of the stereo garage. When LIMs are supplied with power supply, the moving frame is moved in the longitudinal direction to reach the required parking space.

a)



(a) Diagram of a unit of stereo garage

b)



(b) Vertical view of stereo garage

Fig. 1. The stereo garage driven by LIMs

Figure 2 shows the lifting platform, which includes four same LIMs, moving crossbeam, car carrying plate and two electromagnets. The movable primaries of all LIMs are fixed below the moving crossbeam and connected in parallel, and the stationary secondaries of LIMs are mounted on the lifting platform. The air gap length is kept by two linear bearings. Above the moving cross-beam, two electromagnets are mounted, which are supplied with DC current. The corresponding cores are attached to the side of each car carrying plate. Compared to a traditional stereo garage, this stereo garage mounts all electrical equipments on the lifting platform, so the structure of all parking spaces are very simple because each only carries the car carrying plate. In both directions, encoders are fixed to obtain the running velocity, and then the vector control method is adopted.

During the process of storing or taking the car, the moving frame and lifting platform can work together to find the parking space as soon as possible. Then the moving crossbeam is driven to take the car.

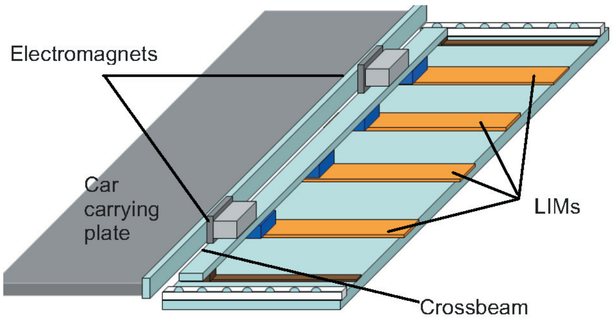


Fig. 2. Diagram of lifting platform

When the car is taken from the stereo garage, the LIMs are connected with power supply, and then drive the moving frame and moving crossbeam to the corresponding parking space together with the lifter. When the moving crossbeam is close to the car carrying plate, the electromagnets are supplied with DC current to attract the car carrying plate. After that, the moving crossbeam runs in the opposite direction driven by LIMs, so that the car carrying plate with the car is taken out of the parking space to the lifting platform. Finally, the car is sent to the exit together with the lifter and moving frame. The process of storing the car is just the opposite. Therefore, depending on the movement of LIMs, the car can move rapidly in order to lower the car access time.

3. Design feature of LIMS

To the LIM in this application, the primary length cannot be longer than the width of the moving crossbeam. Since the width of the moving crossbeam should be as small as possible for the reduction of both width and weight of the lifting platform, the primary length is also limited. Under limited primary length, the primary width is direct proportional to the thrust force. If only one LIM is adopted, it becomes too large. For decreasing the primary width per LIM, even numbers of LIMs are adopted, such as 2, 4, 8, 10 etc., which are symmetrically mounted below the moving crossbeam.

The stroke of the LIM is almost the width of the car, so the running velocity cannot be high due to limited stroke and large weight. That is to say, the rating velocity of LIM is low. Considering the pole pitch of the LIM with traditional overlapping windings, the frequency of the power supply is also low. Therefore, the LIM should be designed at a low frequency.

If four LIMs are adopted in the moving crossbeam, according to the application requirement, the rated velocity, voltage and starting thrust force of each designed LIM are 0.8 m/s, 380 V and over than 666 N respectively. Since the width of the moving crossbeam is given, the primary length is fixed, and then the pole pitch and pole number are also obtained. It should be noticed, the transverse effect do not be considered since the secondary width can be wide enough.

The same LIMs are also applied in longitudinal moving mechanism for a convenient application. In each side, there are also four LIMs adopted. According to the required velocity 0.8 m/s, the suitable frequency of a power supply is 11.5 Hz. At this frequency, the voltage is at a full value, 380 V. The LIM can be designed based on the equivalent circuit, which can well consider the static longitudinal effect, dynamic longitudinal effect and secondary back-iron loss [7].

4. Parameter analysis and dynamic feature

The FEM of this LIM is shown in Figure 3. In this model, the velocity of the primary is assumed zero, and the phase windings are supplied with full voltage 380 V with $f = 11.5$ Hz. In addition, the end windings are considered by the effective impedance, which is calculated in the former equivalent circuit method.

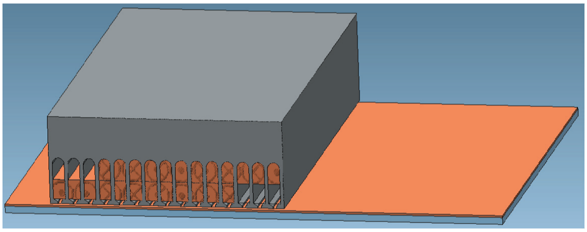
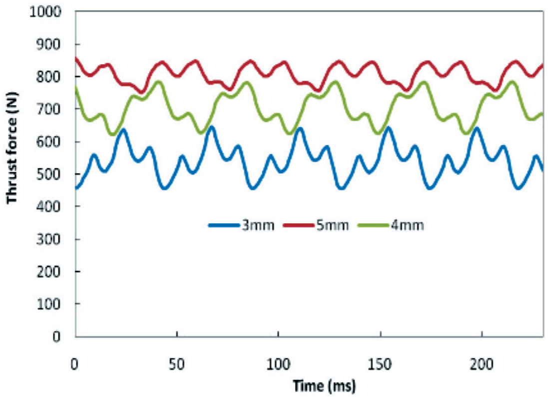


Fig. 3. The FEM of designed LIM

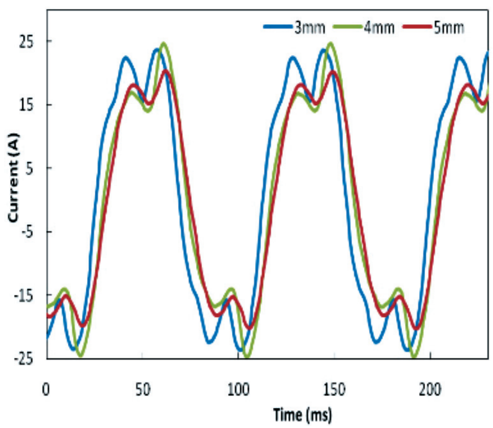
The thrust force of different tooth width is analyzed, shown in Figure 4. Apparently, when the tooth width is equal to 3 mm, the performance of the LIM becomes worse because the thrust force decreases rapidly and the current also increases. This is caused by magnetic field saturation. When the tooth width is over 5 mm, the thrust force and current almost maintain constant.

Furthermore, compared to the tooth width of 4 mm and 5 mm, the thrust force of the former is a little higher and its current is also a smaller. Of course, the current density is also slightly improved due to smaller slot area.

It should be noticed, that the tooth width should be bigger than the normal LIM due to a low frequency power supply. The reason is the big flux density due to full voltage and low frequency. Of course, the current density is also affected by the tooth width.



a) thrust force



b) current

Fig. 4. Locked thrust force of LIM with different tooth width

The height of yoke is much higher because the lamination is assembled by bolt. If it can be assembled by the welding method, the height of the yoke can be decreased a lot. According to the design analysis, the primary height can be reduced to 60 mm. Both thrust force and three phase current almost keep constant. Therefore, the magnetic field of yoke is smaller than the saturation value.

If the velocity of the primary is set to zero, the locked thrust force and phase currents can be obtained. Three phase currents are asymmetrical and also have a lot of harmonic components. The currents of phase A and phase B are bigger due to small mutual inductances. To phase C, the fundamental component is 13.15 A, which is also bigger than that of the equivalent circuit method. Figure 5 shows the thrust force. As it can be seen, the average thrust force is 700 N.

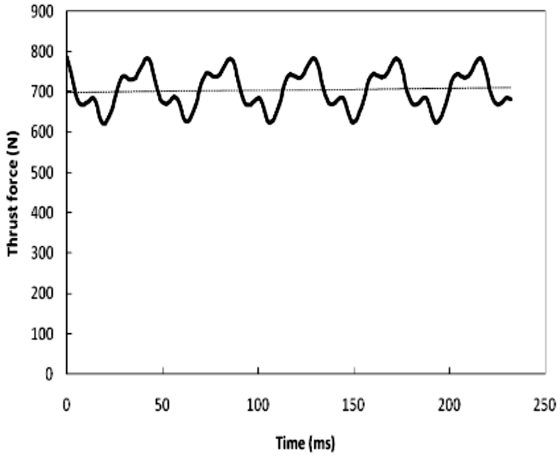
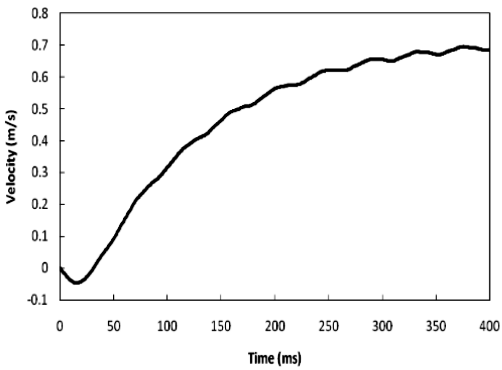
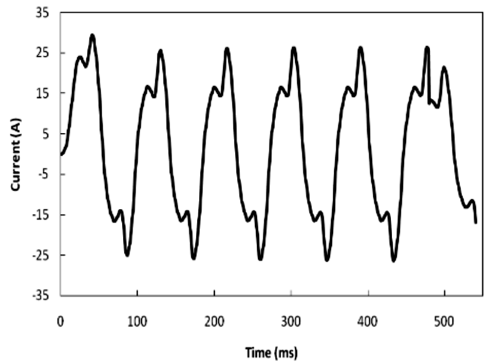


Fig. 5. The locked thrust force at full voltage

Figure 6 shows the dynamic velocity of LIM at load 300 N. The static velocity is 0.7 m/s, so the slip is 0.4. During the starting procedure, the currents do not decrease rapidly as normal LIM, only have a slight change.



a) velocity curve



b) current curve

Fig. 5. The dynamic velocity and current of LIM at load 300 N

5. Application and measurement

The prototype is made and installed in two 8-layers stereo garages. One has one unit, and the other has three units. Figure 6a) and Figure 6b) show the fomer LIM primary and lifting platform. This 8-layers stereo garage has two parking spaces in the same layer, so that it is without the moving frame, shown in Figure 6c). It shows a good performance and has already been operating for two years until now.

At a test platform, the LIM is locked and supplied with 380 V, 11.5 Hz three phase voltage, and then the locked thrust force can be measured. Table 1 lists the measured value of six LIMs. As it can be seen, the average value of the current is 12.2 A, and the average thrust force is 702 N. Apparently, the measured current and thrust force are close to those of the designed values. The small error may be caused by the installation of a processing precision.

In stereo garage, the given maximum value of velocity, accelerator and decelerator are 0.8 m/s, 0.4 m/s^2 and 0.8 m/s^2, respectively. That is to say, the whole time is 5 s. The maximum time of taking car to lifting platform is only 10 s, which is smaller than that of the lifting time. Therefore, the car access time only mainly depends on the lifter. In the 8-layers stereo garage without moving frame, it is only 30 s, which is much lower than the traditional one.

a) LIM

b) lifting platform

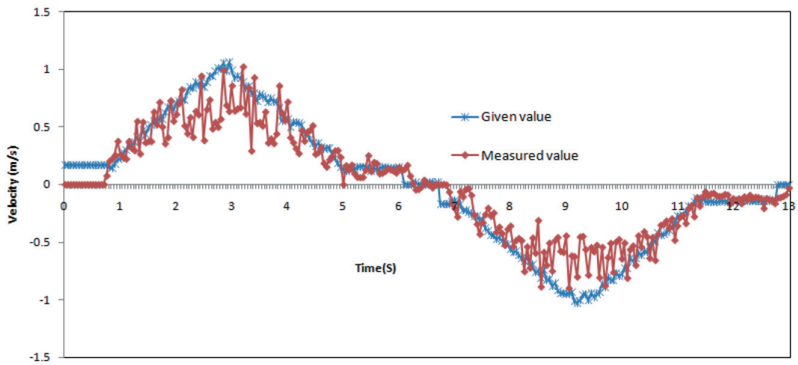
c) tereo garage

Fig. 6. The prototype LIM for stereo garage

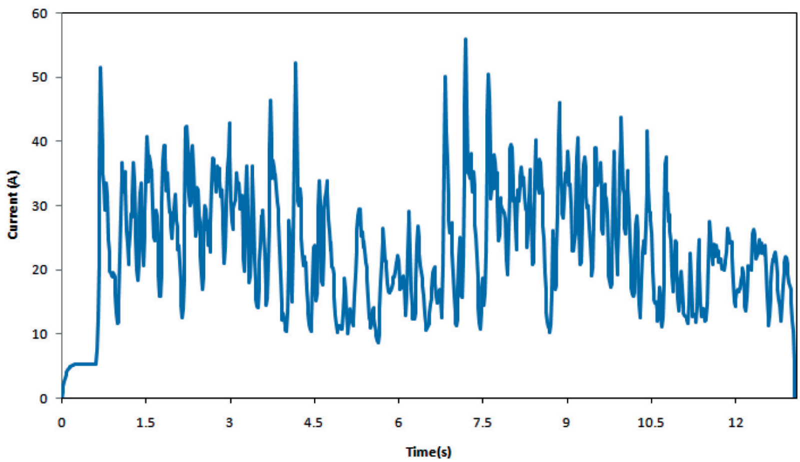
Table 1. Measured thrust force

Motor number	Current (A)	Thrust force (N)
1	12.6	686
2	12.8	696
3	11.5	725
4	11.5	696
5	13	725
6	11.8	686

When the moving crossbeam takes or stores the car carrying plate without a car, the measured maximum velocity, voltage, frequency and current are 317 V, 11.6 Hz and 9 A respectively. When the car shall be saved, the car carrying plate has to be taken first. Therefore, the crossbeam moves towards the car carrying the plate first, and then takes the car carrying plate without the car to the lift platform. The corresponding velocity response curves and current of all four LIMs are shown in Figure 7.



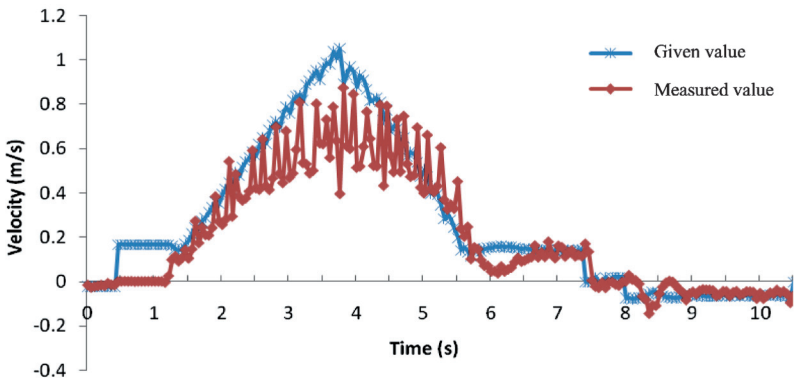
a) Velocity response



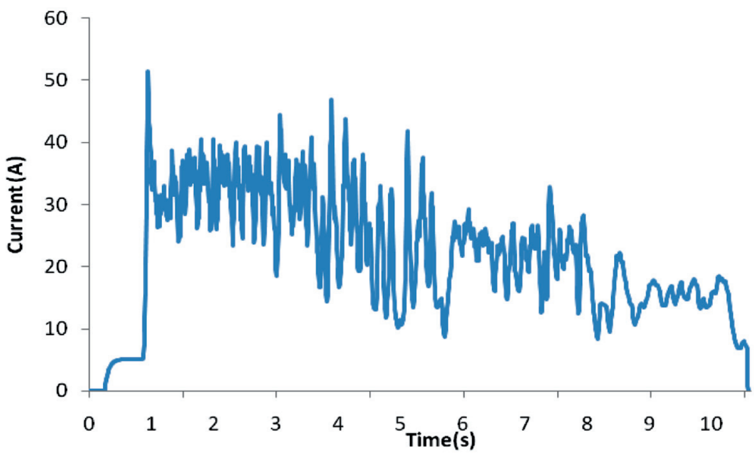
b) Current of all four LIMs

Fig. 7. The velocity response and current of LIMs when taking car carring plate

Apparently, the velocity of the moving crossbeam arrives at 0.8 m/s at no load, only with the crossbeam moving. However, it decreases a little bit when the moving crossbeam moves with the car carrying plate with the car. Of course, the thrust force still should be improved to reach 0.8 m/s if taking or storing cars. The current only changes a little bit when the moving crossbeam takes the car carrying plate. So the car carrying plate is not heavy.



a) Velocity response



b) Current curve

Fig. 8. Velocity and current when taking a car

Figure 8a) shows the velocity response curves when taking a car, whose weight is 1.4 t. As it can be seen, the car access time is still almost 5 s. Figure 8b) shows the current of all four LIMs. Apparently, the sum of four LIMs are 30 A when the LIMs accelerate, which is higher than that of Figure 7b). If the stereo garage shall take a heavy car, the current will improve further.

6. Conclusions

The LIMs are the most appropriate candidates for huge, fast and intelligent stereo garages. This paper develops a novel stereo garage driven by LIMs, which is designed at a low frequency. LIMs are adopted to drive not only the moving crossbeam, but also longitudinal moving frame. Two 8-layers stereo garages with these LIMs have been developed. One has only one unit and also does not have a moving frame, the other has three units and three moving frames. The former one already showed a fine operating performance for two years.

The LIM is designed according to electrical equivalent circuit method. Based on FEM, the influences of key structure parameters and the dynamic performance are investigated. For this LIM, the tooth width apparently affects the thrust force due to a relative bigger flux density compared to a normal LIM. Therefore, the tooth width cannot be as small as that of a normal LIM. The predicted results are validated by measured results of a prototype.

Acknowledgements

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