Application of levitation frame with mid-set air spring on maglev vehicles

ZHANG Min MA Weihua LUO Shihui

Traction Power State Key Laboratory, Southwest Jiaotong University, Chengdu, China

Corresponding author: MA Weihua
Email: mwh@swjtu.edu.cn

Abstract: The vehicle-guideway coupled vibration (VCV) is always an important problem for the medium-low speed maglev vehicle; to alleviate the problem, a newly typed levitation frame with mid-set air spring (LFMAS) is presented, and the lower dynamic interaction of which with the guideway is explained by motion equation. By comparing the running performance of the LFMAS and the levitation frame with end-set air spring (LFEAS), the effectiveness of the LFMAS on reducing the VCV problem is proved. The results show that the resistance required to adjust the same angle of the LFMAS is $2k_1\dot{\theta} + 2cl\dot{\theta}$ smaller than that of the LFEAS; the new-generation medium-low speed maglev with LFMAS can reach 121 km/h on the Shanghai Lingang test line, and can levitates stably half an hour on the turnout; in all line operating conditions, the vehicle's transverse and vertical stability indicators are less than 2.5, reach the excellent level. The LFMAS exhibits stronger levitation bearing capacity and track adaptability attributing to the release of the ends degree of freedom, which can effectively reduce the influence of the VCV effect on the maglev vehicle.

1. INTRODUCTION

Medium-low speed maglev vehicles have the advantages of small turning radius, strong climbing ability, low noise and comfortable seat, etc., having good prospects and booming trends, and there are 4 operation lines in the domestic and overseas. The VCV problem is always a barrier on the way of the development of the medium-low speed maglev; the running mechanism is too sensitive to the guideway, resulting in levitating failure easily. In order to relieve the VCV effect [1-2] on the vehicle, domestic and foreign scholars have done a lot of studies. Starting from the levitation control algorithm, Cui et al. [3,4] compensated the levitation system, introduced the flux feedback control scheme, analyzed the influence of the levitation control algorithm and the main parameters on the levitation stability, and improved the robustness of the levitation system against load changes. Starting from the track beam structure, Lee et al. [5,6] established a vehicle-bridge coupling numerical model, and discussed the importance of dynamic coupling analysis of maglev vehicle bridges, pointed out that reasonable rail beam structure characteristics and levitation control algorithm have great significance to suppress vehicle-rail coupling vibration.

A lot of significant achievements have been made in the above researches, but the problem of VCV has not been completely solved. High quality and stiffness requirements of the running mechanism to
the track makes the track cost higher and the construction process more complicated. Based on the above research, this paper puts forward the research direction of optimizing the running mechanism from the perspective of optimizing the vehicle structure; the team of professor Luo from southwest jiaotong university carried out a decade-long study to explore a new-type running mechanism with better track adaptability and bearing capacity, its low-dynamic-interaction mechanism is explained by the motion equation in this paper; after long-term operation on the test line, the strong levitation bearing capacity and track adaptability of which are been proved.

2. Two kinds of levitation frames

The medium-low speed maglev vehicle is mainly composed of two parts: car body and levitation frame. The levitation frames of the current operating vehicles are all LFEAS, in which levitation frame consists of two levitation modules, and the levitation modules are connected by two sets of anti-roll devices, as shown in figure 1; the levitation module mainly comprises longitudinal beam, linear induction motor and levitation electromagnet. Each end of the longitudinal beam has an air spring; one levitation frame has four air springs to support the car body. The LFEAS is sensitive to the mass and stiffness of the track as well as the variation of vehicle load, whose complex structure and large dead weight reduce the carrying capacity of the vehicle, and limit the installation space of the linear induction motor, resulting in insufficient traction capacity.
The main forces the LFEAS subjected are shown in Fig. 2, from top to bottom, including gravity of the car body whose direction is downward; the normal force generated by linear induction motor may be up or down with the change of the speed and slip frequency; the suction force supplied by levitation electromagnets is upward. The forces generated by the linear induction motor and levitation electromagnets are uniform; the gravity of the car body transferred by air spring can be regarded as concentrated. Considering reducing the number of forces acting on the levitation module to reduce the interaction between the levitation frame and the track, the number of air spring on a levitation module is reduced from two to one, so that the vertical motion of the levitation module ends become freer. Specifically, the structure shows that two air springs at both ends of the levitation module are reduced to one air spring in the middle of the longitudinal beam, as shown in Fig. 3; the forces the levitation module subjected is shown in Fig. 4.

Air springs on the LFMAS is placed at the middle of the longitudinal beam, the linear induction motor installed in the LFMAS can be get longer, resulting in the increasing of the tractive force. The lateral resetting force of the levitation module is mainly provided by the levitation electromagnets, which has the function of self-regulating guided resetting. The anti-roll devices connecting two levitation modules is designed to inhibit the rotation of the levitation module around the x axis and allow two levitation modules to have certain dislocation in the longitudinal, lateral and vertical directions, as shown in Fig. 1 and Fig. 3. In terms of these four degrees of freedom, one set of anti-roll device can achieve the same effect as two sets; when the anti-roll device is two sets, the constraint effect on the rotation degree of freedom of the levitation module around z and y axis is greater than that of one set of anti-roll device. The rotation of the levitation module around z axis mainly occurs when passing curves and be reset by the lateral force supplied by the levitation electromagnets. The rotation around y axis mainly occurs in the levitation adjustment process, and the restraint will hinder the levitation adjustment and increase the burden of the levitation system. Therefore, one set of anti-roll device can achieve the same functionality while reducing the coupling effect of levitation adjustment.

3. Vertical motion equations

3.1 vibration model
The vertical bearing forces of the levitation module from top to bottom are gravity of the car body, normal force of the motor and levitation force of electromagnets. The value of the normal force can be controlled by traction inverter, so its influence can be neglected. The vibration model of the levitation module is shown in Fig. 5. The force from the air spring can be considered concentrated. The levitation force is considered uniform, and its local value is closely related to the size of the air gap and the current, as well as the arrangement of the coils.

In the process of starting levitation, the levitation module can be regarded has only translational motion without rotation. At this point, the levitation force is distributed symmetrically along the longitudinal beam; and the module doesn't have eccentric torque due to the uniform distribution of the force; at the same time the equivalent levitation force $F_l$ is applied at the center of the levitation module and $e$ is 0.
In the running process, there are track excitations such as the irregularity of the track and the malposition of the rail joint. When passing through the excitation section, the sensors on the same levitation module feed different air gap size and acceleration to the corresponding controller, resulting in different current values in the four coils of the electromagnet, so as to achieve the purpose of levitation adjustment. The levitation module has both translation and rotation in the adjustment process; generally, $F_I$ is eccentric and $e$ is not 0. When the levitation force on the right side of the levitation module is greater than the left one, $e$ is on the right side of the center point, and vice versa. $K$ is the stiffness of the air spring on LFMAS, and $k$ is that of the LFEAS.

### 3.2 Motion equation

The biggest difference between the structure of the LFEAS and the LFMAS is the position and number of the air spring on a levitation module; there are two air springs at both ends of the levitation module for LFEAS, while only one air spring in the middle of the levitation module for LFMAS. In order to adapt the rail changes, the levitation module is being adjusted constantly to maintain the air gap size. The levitation module has vertical and lateral movement relative to the track, the lateral malposition is mainly caused by the curve passing; and the vertical movement is the main motion, which is translation motion coupled with rotation. The motion equations of the two kinds of levitation frames are compared in this section, and the coordinate center selected to analyze the equations is the middle of the longitudinal beam.

Figure 5. Vibration model of levitation module

Figure 6. Vertical bearing force of the levitation frame
The air spring position of the LFMAS, which is at the center of the longitudinal beam, is taken as the origin of coordinates; the motion equation of the LFEAS is expressed as follows:

\[
m\ddot{z} = -k(z - l\dot{\theta}) - k(z + l\dot{\theta}) + k_i(z + e\dot{\theta}) - 2cz \tag{1}
\]

\[
J\ddot{\theta} = k(z - l\dot{\theta})l - k(z + l\dot{\theta})l + k_i(z + e\dot{\theta})e - 2cl\dot{\theta} \tag{2}
\]

Simplified as

\[
m\ddot{z} = -2kz + k_i(z + e\dot{\theta}) - 2cz \tag{3}
\]

\[
J\ddot{\theta} = -2kl^2\theta + k_ie(z + e\dot{\theta}) - 2cl\dot{\theta} \tag{4}
\]

The matrix is shown as

\[
\begin{bmatrix}
m & 0 \\
0 & J
\end{bmatrix}
\begin{bmatrix}
z \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
2c & 0 \\
0 & 2cl
\end{bmatrix}
\begin{bmatrix}
\dot{z} \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
2k - k_i & -k_ie \\
-k_ie & 2kl^2 - k_i e^2
\end{bmatrix}
\begin{bmatrix}
z \\
\dot{\theta}
\end{bmatrix}
= 0 \tag{5}
\]

The vertical motion equation of the LFMAS is shown as follows:

\[
m\ddot{z} = -Kz + k_i(z + e\dot{\theta}) \tag{6}
\]

\[
J\ddot{\theta} = k_i(z + e\dot{\theta})e \tag{7}
\]

The matrix is shown as

\[
\begin{bmatrix}
m & 0 \\
0 & J
\end{bmatrix}
\begin{bmatrix}
z \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
C & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{z} \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
K - k_i & -k_ie \\
-k_ie & -k_i e^2
\end{bmatrix}
\begin{bmatrix}
z \\
\theta
\end{bmatrix}
= 0 \tag{8}
\]

When the air spring stiffness of the LFMAS is 2 times of that of the LFEAS, that is \(K = 2k\), the equation (8) becomes

\[
\begin{bmatrix}
m & 0 \\
0 & J
\end{bmatrix}
\begin{bmatrix}
z \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
2c & 0 \\
0 & 2cl
\end{bmatrix}
\begin{bmatrix}
\dot{z} \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
2k - k_i & -k_ie \\
-k_ie & 2kl^2 - k_i e^2
\end{bmatrix}
\begin{bmatrix}
z \\
\dot{\theta}
\end{bmatrix}
= 0 \tag{9}
\]

As can be seen from the comparison between equation (5) and (9), the vertical translational equations is exactly the same while the rotational equation is different, which means that the resistance needed to adjust the same rotation angle for LFEAS is \(2kl\dot{\theta} + 2cl\dot{\theta}\) bigger than that for LFMAS.

When the rotation angle of the levitation module \(\theta\) is 0, means the levitation module has only translational motion without any rotation; this adjustment state generally exists in the starting levitation process. The motion equation of the LFEAS is:

\[
m\ddot{z} = -2kz + k_i z - 2cz \tag{10}
\]

The motion equation of the LFMAS is:

\[
m\ddot{z} = -Kz + k_i z - Cz \tag{11}
\]

When the air spring stiffness of the LFMAS is 2 times of that of the LFEAS, the motion equations of the two kinds of levitation modules are identical in the starting levitation process.

As can be seen from equations (5) and (9), the mass matrix and damping matrix of the vertical motion equations are diagonal, and the stiffness matrix is non-diagonal, which fails to achieve simultaneous decoupling. At the same time, it can be seen that the vertical translational equations of the two kinds of levitation modules are the same, but the rotational equation is different. The resistance needed to adjust the same rotation angle for the LFEAS is \(2kl\dot{\theta} + 2cl\dot{\theta}\) bigger than that for the LFMAS. The optimization of the levitation frame structure releases the ends degree of freedom, resulting in the difference of the motion equation of the levitation module; and the force needed to overcome when rotate the same angle is smaller.
4. Application

![LFEAS Image](image1.png)

![LFMAS Image](image2.png)

Figure 7. Application of the two kinds of levitation frame

As shown in Fig. 7 (a), the LFEAS has been applied on two maglev operation lines in China (Beijing S1 line and Changsha airport line), but its operating speed is less than 100km/h. The LFMAS independently developed by Southwest Jiaotong university is shown in Fig 7 (b). After more than 2 years of test line operation, it has been proved that the LFMAS has stronger levitation-bearing capacity and track adaptability, and its sensitivity to the track is lower than that of the LFEAS. Limited to the length of the test line, the test speed of the LFMAS on the test line has reached 121km/h, and can levitates stably half an hour on the turnout, which prepare for its marketization and promotion.

In order to test the levitation stability of the LFMAS shown in Fig. 7 (b) with various speeds and line conditions, the line running tests are carried out. On the test line with a total length of 1.7 km, the vehicle passes the R50m curve at the speed of 10 km/h, passes the R75m curve at the speed of 25 km/h, go through the straight line and turnout at the speed of 80 km/h and 100 km/h respectively, and climbs the slope at the speed of 25 km/h. The test results are shown in Fig. 8 and Fig. 9.

| Stability level | Evaluation | Stability indicator |
|-----------------|------------|---------------------|
| Level 1         | Excellent  | \( W < 2.5 \)       |
| Level 2         | Good       | \( 2.5 < W < 2.75 \) |
| Level 3         | Pass       | \( 2.75 < W < 3 \)  |

Table 1. Evaluation criteria of the vehicle stability indicator
Fig 8 shows the changes of the lateral and the vertical accelerations of the car body. In all operation conditions, including R50 m small radius curve, turnout and the hill with 0.07 slope, the largest vertical acceleration is less than 0.2 m/s², and the maximum lateral acceleration is less than 0.1 m/s², far less than the comfort requirements [7] of the maglev vehicle which requires that the lateral acceleration is less than 1 m/s², vertical additional upward acceleration is less than 0.5 m/s², vertical downward additional acceleration is less than 1 m/s². There is no abrupt change of the acceleration when passing the small radius curve line and turnout, which indicates that the LFMAS has better track adaptability, lower sensitivity to the track, and can levitates stably more easier after the decoupling of the ends of the levitation module.
The speed of the vehicle is higher when running in the linear track, so its acceleration amplitude a little larger than other working conditions. Fig. 9 shows the further analysis of the lateral and vertical stability. In the whole line and running conditions, the lateral and vertical stability indicators of the vehicle are less than 2.5, reach the excellent level.

5. Conclusion

1) The optimization of the levitation frame structure releases the ends degree of freedom, resulting in the difference of the motion equation of the levitation module. The resistance required to adjust the same angle of the LFMAS is $2kl^2\theta + 2cl\dot{\theta}$ smaller than that of the LFEAS, which indicates that the LFMAS can adapt the rail more easily in the levitation process.

2) The new-generation medium-low speed maglev adopting the LFMAS can reach 121km/h on the Shanghai Lingang test line, and can levitates stably half an hour on the turnout; The transverse and vertical stability indicators all reach excellent level. The research proves that the LFMAS exhibits stronger levitation-bearing capacity and track adaptability attributing to the release of the ends degree of freedom, can effectively reduce the influence of the VCV effect on the maglev vehicle.

References

[1] LEE H W, KIM K C, JU L. Review of maglev train technologies[J]. IEEE Transactions on Magnetics, 2006, 42(7): 1917-1925.
[2] Zhang M, Luo S H, Gao C and Ma W H. Research on the mechanism of a newly developed levitation frame with mid-set air spring [J]. Vehicle System Dynamics, 2018,1-21

[3] CUI P, LI J, ZHANG K, et al. Design of the suspension controller based on compensating feedback linearization[C]. International Conference on Measuring Technology and Mechatronics Automation, 2010, (1): 1056-1059.

[4] Li J H, Li J. A practical nonlinear controller for levitation system with magnetic flux feedback[J]. Journal of Central South University, 2016, 23(7): 1729-1739.

[5] LEE J S, KWON S D, KIM M Y, et al. A Parametric study on the dynamics of urban transit maglev vehicle running on flexible guideway bridges[J]. Journal of Sound and Vibration, 2009, 328(3): 301-317.

[6] CAI Y, CHEN S S, ROTE D M, et al. Vehicle/guideway dynamic interaction in maglev systems[J]. Journal of Dynamic Systems, Measurement, and Control, Transactions of the ASME, 1996, 118(3): 526-530.

[7] Lin Z, Zhou D. Brief Introduction of the Track of Shanghai Maglev[J]. China Railway Science, 2003, 24(1): 104-107