Modeling and Analysis of Suspension Frame of Maglev Train

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Abstract. Based on the acceleration feedback system, the vertical dynamic model of the low-speed maglev train is established. By decoupling the suspension frame module, the author conducted a stress analysis of the single-sided and the entire suspension system, and established a system dynamics model of the suspension frame. The suspension controller is designed using classic PD control and acceleration feedback control methods. Then, the author used Simulink to create a dynamic simulation analysis program to analyze the dynamic performance of the suspension system affected by track misalignment and external disturbance forces, and analyze the impact of the suspension frame's parameter design on the suspension system performance.

1. Introduction
Today, maglev trains are rapidly developing high-speed ground transportation. The train has no mechanical contact with the track during operation. It is comfortable, fast and highly safe, which has aroused strong research interest. Suspension is the key operation and control unit of maglev train, and the structure is separated during operation. This article focuses on the vertical dynamics modeling of the low-speed maglev train suspension system, and analyzes the dynamic performance under various external disturbances (such as misalignment of track connections, external forces, etc.). The controller is designed based on PD control and acceleration feedback control mode. Real-time acceleration signal realizes acceleration feedback. This article provides specific design parameters and methods for suspension frames. Through the simulation method, the important parameters of the suspension frame, such as the distance of the suspension sensor, the vertical distance of the air spring and the vertical distance of the anti-tipping beam, are verified to affect the performance of the suspension. Suspension system.

2. Dynamics Modeling of the Suspension System
The suspension system connects the suspension module to the anti-roll beam. First, we decouple the suspension system and build a dynamic simulation model of the unilateral suspension. It is assumed that the suspension is a rigid body, that is, elastic deformation is not considered, so the system is simplified as a vibration system connected by elastic damping components. It is further assumed that the carriage connected to the suspension by the air spring is in a stationary state, and the weight of the carriage and vehicle equipment is evenly distributed in each air spring. One side of the suspension is assumed to be a line model with a uniform mass distribution, and the force acts on the geometric centerline. The stress analysis of vertical movement and nodding movement is shown in Figure 1
Analyze the unilateral suspension, assuming that the force direction is vertically downward and the positive direction, and the torque direction is vertical and outward, the dynamic equation of the unilateral suspension is:

\[ m\ddot{z} = mg + fd + F_{v1} + F_{v2} - F_{e1} - F_{e2} \]  \hfill (1)

\[ J\ddot{\theta} = F_{e2} \cdot \frac{L_{mag}}{4} - F_{e1} \cdot \frac{L_{mag}}{4} + F_{v1} \cdot \frac{L_s}{2} - F_{v2} \cdot \frac{L_s}{2} + fd \cdot L_d \]  \hfill (2)

\( F_{e1} \) and \( F_{e2} \) are the electromagnetic force of the suspension electromagnet, \( F_{en} = K_e \cdot i^2 / z^n \), and the ratio \( K_e = \mu_0 \cdot N^2 \cdot A / 4 \) is related to the number of windings and the core area. It can also be obtained by rated current and rated suspension air gap. Among them, \( z^n (n = 1, 2) \) is the current of the two sets of electromagnetic coils and the air gap of the sensor. \( F_{v1}, F_{v2} \) are the force of the air spring. \( F_{vn} = K_v \cdot n + C_v \cdot n + Mg / k \), \( K_v \) and \( C_v \) are the stiffness and damping of the air spring. \( M \) is the total mass of the bracket and on-board equipment. \( k \) is the number of air springs connected to the bracket. \( m \) is the mass of the suspension module. \( fd \) is external interference. \( \theta \) is the rotation angle of jog. \( J \) is the moment of inertia, \( J = L_{mag} \cdot m / 12 \), and \( L_{mag} \) is the length of the suspension electromagnet. \( L_s, L_d \) and \( L_{sen} \) are the vertical distance of the air spring, the distance between the external interference and the center of mass, and the distance of the suspension sensor.

The dynamic model of the suspension system is based on the model of the one-sided suspension. The suspension frame modules are connected by anti-tipping beams. When the suspension frame module is twisted, the anti-overturn spring will elastically deform and generate interaction forces. The stress analysis of the suspension system is shown in Figure 2.

**Fig 1.** Stress analysis of a unilateral suspension frame.

Analyze the unilateral suspension, assuming that the force direction is vertically downward and the positive direction, and the torque direction is vertical and outward, the dynamic equation of the unilateral suspension is:

\[ m\ddot{z} = mg + fd + F_{v1} + F_{v2} - F_{e1} - F_{e2} \]  \hfill (1)

\[ J\ddot{\theta} = F_{e2} \cdot \frac{L_{mag}}{4} - F_{e1} \cdot \frac{L_{mag}}{4} + F_{v1} \cdot \frac{L_s}{2} - F_{v2} \cdot \frac{L_s}{2} + fd \cdot L_d \]  \hfill (2)

\( F_{e1} \) and \( F_{e2} \) are the electromagnetic force of the suspension electromagnet, \( F_{en} = K_e \cdot i^2 / z^n \), and the ratio \( K_e = \mu_0 \cdot N^2 \cdot A / 4 \) is related to the number of windings and the core area. It can also be obtained by rated current and rated suspension air gap. Among them, \( z^n (n = 1, 2) \) is the current of the two sets of electromagnetic coils and the air gap of the sensor. \( F_{v1}, F_{v2} \) are the force of the air spring. \( F_{vn} = K_v \cdot n + C_v \cdot n + Mg / k \), \( K_v \) and \( C_v \) are the stiffness and damping of the air spring. \( M \) is the total mass of the bracket and on-board equipment. \( k \) is the number of air springs connected to the bracket. \( m \) is the mass of the suspension module. \( fd \) is external interference. \( \theta \) is the rotation angle of jog. \( J \) is the moment of inertia, \( J = L_{mag} \cdot m / 12 \), and \( L_{mag} \) is the length of the suspension electromagnet. \( L_s, L_d \) and \( L_{sen} \) are the vertical distance of the air spring, the distance between the external interference and the center of mass, and the distance of the suspension sensor.

The dynamic model of the suspension system is based on the model of the one-sided suspension. The suspension frame modules are connected by anti-tipping beams. When the suspension frame module is twisted, the anti-overturn spring will elastically deform and generate interaction forces. The stress analysis of the suspension system is shown in Figure 2.

**Fig 2.** Stress analysis of the suspension frame system.
Assuming that the direction of the spring tension is positive, the direction of the force is vertically downward and the direction of the torque is vertical and outward, then the dynamic equation of the suspension system is:

\[ m\ddot{z} = mg + fd + Fv_1 + Fv_2 - Fe_1 - Fe_2 - Fm_1 - Fm_2 \]  

(3)

\[ J\ddot{\theta} = Fe_2 \cdot \frac{L_{mag}}{4} - Fe_1 \cdot \frac{L_{mag}}{4} + Fv_1 \cdot \frac{L_s}{2} - Fv_2 \cdot \frac{L_s}{2} + fd \cdot L_d - Fm_1 \cdot \frac{L_b}{2} - Fm_2 \cdot \frac{L_b}{2} \]  

(4)

\( Fm_1, Fm_2 \) are the forces of the anti-overturn spring. \( Fmn = Km \cdot n + Cm \cdot n \), \( Km \) and \( Cm \) are the stiffness and damping of anti-tipping spring respectively. \( n \) is the deformation of the anti-tipping spring. \( Lb \) is the longitudinal distance of the anti-tipping beam.

### 3. Simulation and analysis of the suspension system

According to the dynamic model of the suspension system, the simulation method is used to analyze the stability of the system in the event of rail misalignment or external interference, and to verify the effect of the parameter design of the suspension sensor spacing, air spring vertical distance and longitudinal direction. The distance of the anti-tipping beam depends on the performance of the suspension system. The main parameters of the suspension system are shown in Table 1.

### Table 1. the main parameters of suspension frame system.

| Parameters                                      | Value  |
|------------------------------------------------|--------|
| length of suspension electromagnet              | mm 2720|
| vertical distance of air springs                | mm 2520|
| transverse distance of air springs              | mm 1860|
| spacing of suspension sensors                   | mm 2500|
| longitudinal distance of anti-rollover beams    | mm 2300|
| horizontal distance of anti-rollover springs    | mm 800  |
| weight of suspension module                     | Kg 750  |

The stiffness of the air spring is 50N/m, and the damping coefficient is 10N/(m/s). The anti-overturn spring has a stiffness of 300N/m and a damping of 70N/(m/s). The rated current of the suspension system is 30A, and the rated air gap is 8mm, so the Ke coefficient is equal to 0.0008.

The spacing of the suspension gap sensors of the suspension frame directly affects the acquisition of track interference signals, which requires multiple simulations to verify. The spacing of the suspension gap sensor is set to 2.5m and 1.5m, the rated air gap is 8mm, and the step response of the air gap is 1mm. to observe the frame of the waveform change of the suspension air gap at the same position of the suspension.

Fig. 3 shows that when the distance of the suspension gap sensor is reduced, the change of the suspension gap with respect to the equilibrium position is reduced, and the maximum air gap change of the suspension frame is not detected. The error of the detected value relative to the actual value is large, which may easily cause safety problems. Therefore, the sensors of the suspension should be installed at both ends near the suspension electromagnet to ensure the accuracy of the detection.
The maglev train is connected by 10 sets of suspension modules and 20 air springs. Assuming that each air spring even bears the weight of the train, the longitudinal distance of the air spring will also affect the stability of the suspension. The longitudinal distance of the air spring is set to 2.52m and 1.0m, and the step response of the air gap is 1mm, to observe the waveform change of the suspension air gap at the same position of the suspension.

Figure 4 shows that when the longitudinal distance of the air spring is reduced, that is, when the equivalent lever arm size of the jog action is reduced, the fluctuation of the suspension air gap will increase significantly, and the adjustment time will increase significantly.

The two suspension modules of the suspension frame system are connected to each other by an anti-overturn beam. The parameter design of the anti-rolling beam is directly related to the decoupling of the suspension frame module, thereby affecting the curve performance of the maglev train. We set the longitudinal distance of the anti-tipping beam to 2.3m and 1.5m, and set the step response of the air gap to 1mm to observe the change of the suspension air gap waveform at the same position of the suspension frame.
Figure 5 shows that when the longitudinal distance of the anti-tipping beam is reduced, the peak value of the suspension air gap and the final steady state value both increase. The change of the air gap is less than 1mm, the detection accuracy is reduced, indicating the error of the measured value. Therefore, the longitudinal distance of the anti-tipping beam should be as close as possible to the distance between the suspension sensors to improve the detection accuracy.

When the maglev train is running, the suspension is often subject to external interference. We simulated the situation when the suspension encountered a constant force of 1500 N and a disturbing force of 100 rad/sec in the same direction of gravity. The changes in acceleration and air gap of the suspension system are shown in Figure 6.

![Figure 5](image1.png)

**Fig 5.** Effect of longitudinal distance of anti-rollover beams.

![Figure 6](image2.png)

**Fig 6.** Effect of external disturbance on the suspension frame.
When the suspension is subjected to external forces (constant or changing disturbances), the suspension system is balanced by PD control and acceleration feedback control. Therefore, the suspension system has good dynamic stability. Acceleration feedback control can reduce air gap fluctuations, improve suspension rigidity, and suppress external interference of the suspension system.

4. Conclusions
Use the decoupling method to perform stress analysis and establish the dynamic equations of the single-side suspension and suspension system. The classic PD control and acceleration feedback control methods are used to form a closed-loop feedback control system. Simulink was used to establish the vertical dynamic model of the suspension. The effects of track misalignment and external disturbance on the suspension system and its dynamic stability were analyzed. The specific parameters of the suspension were given to verify its important impact on the suspension. The system provides a theoretical basis for the selection of suspension parameters.

Acknowledgments
This work was financially supported by Funds for Young Scientists of Civil Aviation Flight University of China (No. Q2018-128).

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