Design and Analysis of Maglev Support System for Vacuum Tube Maglev Transportation

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***Abstract*—Vacuum Tube Maglev Transportation significantly reduces the air resistance and eliminates the effects of mechanical friction. With its speed, low energy consumption and other advantages have attracted much attention. The structure and characteristics of its magnetic suspension support are one of the hot research issues. In this paper, an EDS&EMS hybrid support is used. The permanent magnet electrodynamic suspension provides the main levitation and guidance force, and the electromagnetic suspension is used to improve the stability of the support. The physical and simulation models of the support structure are established. Through analysis and simulation, the influence of bearing capacity on air gap and velocity is studied. The results of the two methods are basically consistent. Magnetic field distribution was analyzed in 2D static and transient magnetic fields by ANSYS Maxwell. The causes and trends of errors in analytical methods and simulations are analyzed, which provided a certain foundation for the study of vacuum tube maglev transportation.**

I. INTRODUCTION

The innovation and development of modern transportation can't be separated from high speed, high efficiency and energy saving. In particular, people's pursuit of speed and efficiency continuously promotes the speed of transportation vehicles again and again. Shanghai maglev train is suspended, guided and driven by electromagnetic force. It reaches 430 km/h, faster than any commercial vehicle, and more stable and quieter [1]. But for ground transportation, it is limited by the dense atmosphere. With the increase of speed, especially when the speed exceeds 300 km/h, there will be many problems that can be ignored at low speed, at this time the strong aerodynamic drag and aerodynamic noise hindered speed further improvement [2-4]. Although the maglev train uses electromagnetic force suspended above the orbit, the friction resistance of the wheel and the track is eliminated, but its speed is still limited to the influence of the atmosphere, which is difficult to be further improved.

To solve the above problems, the train can be run in the vacuum pipeline, which is equivalent to the plane flying in the stratosphere, and the rarefied atmospheric environment greatly reduces the air resistance. The train running in the vacuum pipeline needs to be suspended in the pipeline to eliminate the influence of mechanical friction. Therefore, different suspension schemes are adopted.

In 2013, Elon Musk proposed Hyperloop alpha with air suspension, which is considered an open source transportation concept [5-6]. Nowadays electrodynamic suspension (EDS) is adopted, which is similar to Inductrack and Magplane, the eddy current due to movement of magnets on conductors produces a repulsive magnetic field to suspend the system [7-9]. At a static or low speed, the levitation force is not enough to counteract the gravity of the train, and wheels are needed to support.

The supporting principle of Swissmetro and Transrapid all belong to electromagnetic suspension (EMS) [10-12]. EMS uses the attraction of electromagnetic force to resist the gravity of the system. Although not statically suspended, dynamic levitation is achieved by continuously changing the current to change the strength of the magnetic field. ETT and Southwest Jiaotong University use high-temperature superconducting materials to achieve suspension, which is self-stabilizing in suspension and guidance, without the need for active control systems [13].

The above schemes are all in the research stage. There are still many difficulties to overcome in the commercial operation of vacuum tube maglev transportation. In this paper, an EDS&EMS hybrid support is used. The permanent magnet electrodynamic suspension (PMEDS) provides the main levitation and guidance force, and the electromagnetic suspension is used to improve the stability of the support. A physical model was established to derive the formula for bearing capacity. To ensure the rationality of the structural design, the simulation of magnetic field was carried out by ANSYS Maxwell to study the influence of design parameters on the magnetic field and support characteristics.

II. STRUCTURE AND MODEL

A. *The structure of EDS&EMS hybrid support*

At present, permanent magnet materials have been steadily increasing in performance and yield through continuous development, and with the introduction of the Halbach array and the third generation of rare earth permanent magnet materials, the use of high remanence permanent magnets as the magnetic field source of EDS to provide sufficient levitation force has become possibly. The focus of EDS technology research is from superconducting EDS to PMEDS. EDS technology is increasingly used in transportation, aerospace, military and other fields. However, due to the shortcomings of insufficient damping of the EDS, it has affected its rapid development to some extent.

Taking the vacuum tube maglev transportation as its application background, a levitation scheme using EDS&EMS

hybrid magnetic levitation support is shown in Figure 1. The EDS support consists of a permanent magnet Halbach array fixed to the vehicle and conductor sheet fixed to the pipe, the slanting arrangement is used to provide the main suspension and guiding force required by the train. The EMS support consisting of the suspension coil fixed to the vehicle and the track fixed to the pipe can increase system damping and improve stability. At low speeds, the vehicle is supported by training wheel and unloaded using the EMS.

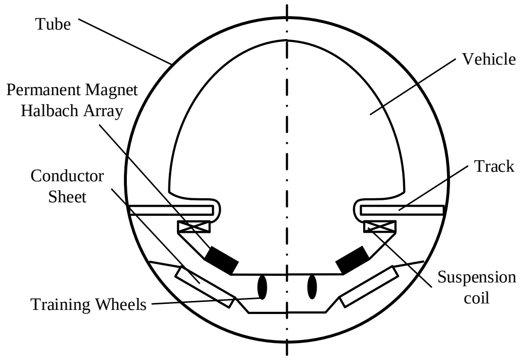


Figure 1. The structure of EDS&EMS hybrid support.

B. *The model of the PMEDS*

The basic principle of the EDS suspension system is related to the electromagnetic induction phenomenon, its model is shown in Figure 2. That is, when there is relative motion between the magnetic field source and the conductor sheet, an induced electromotive force will be generated in the conductor, thereby generating the eddy current that moves with the magnetic field source, and the eddy currents in the conductor will also excite the magnetic field in the surrounding space. Under the interaction of the magnetic field and the magnetic field source, a repulsive force and a resistance hindering the relative movement between the magnetic field source and the conductor are generated. The eddy current excited on the conductor sheet has a direct influence on the lift force and drag force, and then affects the levitation performance of the entire system. Therefore, the characteristics of the permanent magnet Halbach array and the conductor sheet play a key role in the performance of the EDS suspension system.

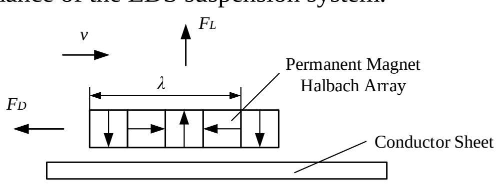


Figure 2. The simplified model of electrodynamic suspension with permanent magnet Halbach array.

Halbach array consists of a plurality of permanent magnet modules of the same magnetization. The magnetization directions of adjacent permanent magnets rotate at a certain angle, so that the magnetic fields are superimposed on one side of the array and cancel each other on the other side, almost zero. In this way, the Halbach array can concentrate the magnetic field energy on one side, maximizing the use of magnetic field energy.

As shown in [14], the peak strength of the magnetic field at reinforced side of the Halbach array is given by:

$$B_0 = B_r(1-e^{-kd})\frac{\sin(\pi / M)}{\pi / M} \tag{1}$$

where Br is the remanence of permanent magnets, d is the thickness of the magnet, M is the number of magnets in one wavelength, and $k = 2\pi / \lambda$, λ is the wavelength of array.

Due to the skin effect, eddy currents can concentrate on the outer surface of the conductor. The skin depth of conductor can be described as:

$$\delta=\sqrt{\frac{2\rho}{\omega\mu_0}} \tag{2}$$

with ρ is the resistivity of conductor, $\omega=kv$,v is the speed of the train, μ_0 is vacuum permeability.

The lift force and the lift-to-drag ratio can be obtained as follows [14]:

$$F_L^{\max} = \frac{B_0^2 A}{\mu_0} e^{-k(2x_1+\Delta_c)} \tag{3}$$

$$F_L = F_L^{\max}\frac{\left(\sqrt{1+\frac{k^4\delta^4}{4}}-\frac{k^2\delta^2}{2}\right)^{3/2}}{k\delta+\left(\sqrt{1+\frac{k^4\delta^4}{4}}+\frac{k^2\delta^2}{2}\right)^{3/2}} \tag{4}$$

$$\frac{F_L}{F_D} = \frac{1}{k\delta}\left(\sqrt{1+\frac{k^4\delta^4}{4}}-\frac{k^2\delta^2}{2}\right)^{1/2} \tag{5}$$

here A is the projected area of one wavelength array on the conductor, x_1 is the distance between the Halbach array and the conductor sheet, Δ_c is the vertical effective thickness of conductor.

From above equation, it can be seen that the maximum lift force is related to the parameters of the structure and the air gap, and not to the speed between the permanent magnet and the conductor. The lift force is related to the structure, air gap and relative velocity, and gradually approaches the maximum lift force as the velocity increases. After determining the structural parameters of the system, the lift-to-drag ratio is proportional to the speed. Increasing the inductance of the conductor and reducing its resistance can also increase the lift-to-drag ratio.

C. *The model of the EMS*

The EMS suspension structure refers to the German TR-08, which uses a long-stator synchronous linear motor. While providing traction to advance the train, the stator core and suspension magnet attract each other to suspend the train. The electromagnetic lift force is only proportional to the square of the excitation current density, independent of the armature current density. Therefore, the magnitude of the lift force can be changed by adjusting the excitation current to compensate the damping of the EDS support, and at the same time, the driving force of the system is not greatly affected. Its simplified model is shown in Figure 3.

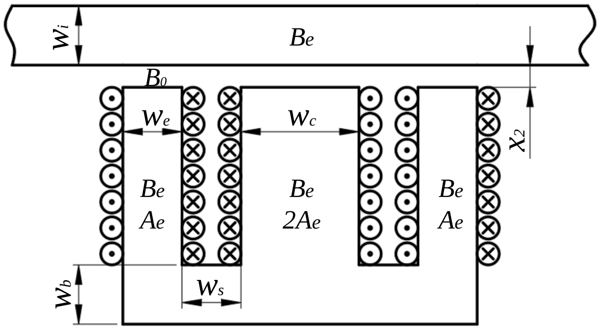


Figure 3. The simplified model of electromagnetic suspension, B is the magnetic flux density of the corresponding position, A_e is the magnetic pole area of the core.

The structural parameters of the core are related, because the magnetic flux through the center E-core is twice of that through the I-core and two sides of the E-core. To simplify the calculation, the correlation between core structure may be expressed as:

$$w_i = w_b = w_e = w_s = w_c / 2 \tag{6}$$

The dimensions according to the above equations are the most material-saving and effective, which may not be designed in accordance with the above equations in practical applications.

Assuming that:

(1) The leakage flux is neglectable.
(2) The magnetic potential energy is even in the gap and core.
(3) The core material is systematic and does not reach magnetic saturation.
(4) The number of coil (N) on the core is equal, and the coil current is equal

By the Maxwell equation, the attractive force between E-core and I-core can be approximately established by the following equation:

$$F = \frac{B_0^2 A}{2\mu_0} \tag{7}$$

here A is the total magnetic pole area in the air gap, B_0 is the magnetic flux density, given by [15]:

$$B_0 = \frac{2Ni}{\frac{l_e A}{\mu_e A_e} + \frac{2x_2}{\mu_0}} \tag{8}$$

where i is the coil current, l_e is the average lengths of the core, μ_e is permeabilities of the core, and A_e is the magnetic pole area of the core. μ_e is much larger than μ_0 and the magnetic flux density can be simplified to:

$$B_0 = \frac{\mu_0 Ni}{x_2} \tag{9}$$

$$F = \frac{2\mu_0 A_e N^2 i^2}{x_2} < \frac{\mu_0 A N^2 i^2}{2x_2} \tag{10}$$

The error of the above formula is not sensitive to the air gap. However, after the air gap is increased, the edge effect makes A larger, no longer equal to A_e. At this time, the magnetic flux density in the air gap is smaller than that of the core. When solving the attractive force with equation (7), $4A_e$ is generally used instead of A, which is the main factor that the force is less than the simulation.

III. SIMULATION

In order to ensure the rationality of the hybrid magnetic levitation support, the magnetic field numerical simulation analysis of PMEDS and EMS was carried out by using finite element analysis software ANSYS Maxwell to study the influence of design parameters on the magnetic field and support characteristics. The simulation model of the PMEDS is shown in Figure 4. The material of the permanent magnet is NdFeB, and the conductor sheet is aluminum.

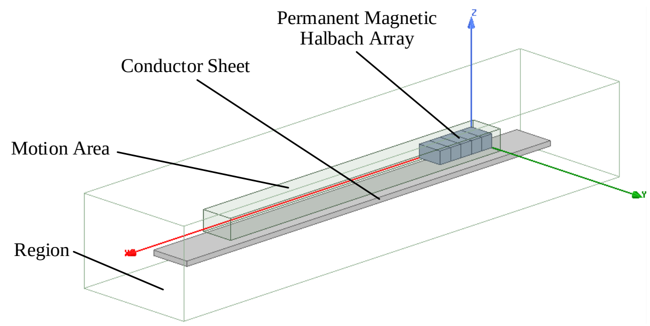


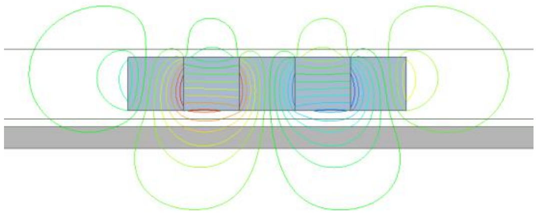
Figure 4. Simulation model of the PMEDS.

Although the simulation model is very simple, the results of the simulation often have large errors, which is due to the division of the mesh. The element should be small enough to ensure the accuracy of the calculation, while the larger speed causes the size of the model to be large, causing the number of grids to rise sharply, so the simulation takes a lot of time and resources. Reducing the motion time of a transient simulation or calculating it in a two-dimensional field can solve this problem to some extent. The data used in this simulation is shown in Table 1.

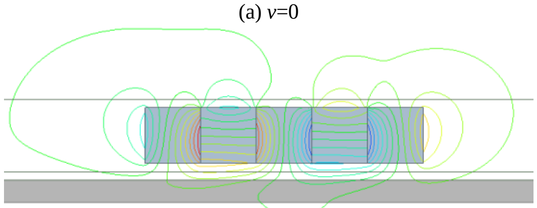
TABLE I. STRUCTURE PARAMETERS OF THE PMEDS

x_1	Air gap	15 mm
d	PM thickness	50 mm
λ	Wavelength	200 mm
M	Wavenumber	4
w	PM width	100 mm
D	Sheet thickness	20mm
W	Sheet width	160 mm

Figure 5 shows the magnetic field distribution of the PMEDS at different speeds in two-dimensional transient magnetic field. When the speed is zero, it can be seen that the magnetic field is strengthened on the lower side of the Halbach array. When the permanent magnet moves, it interacts with the eddy current field to generate lift force and drag force. Since the eddy current has a certain lag, when the speed is increased in the simulation, the lag will become larger and larger, so that the force is continuously reduced.



(a) v=0



(b) v=10m/s

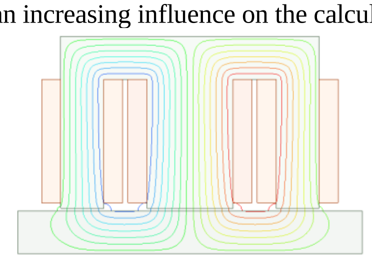
Figure 5. Magnetic field distribution of the PMEDS at different speeds in two-dimensional transient magnetic field.

The structural parameters of the EMS are shown in Table 2. According to width of E-core center leg, most of parameters of the core can be determined, and then the height of the core can be found according to the number of coil. The number of design parameters is large, and different constraints are needed in different occasions. Therefore, the fitness function can be constructed and the optimal solution can be obtained by genetic algorithm.

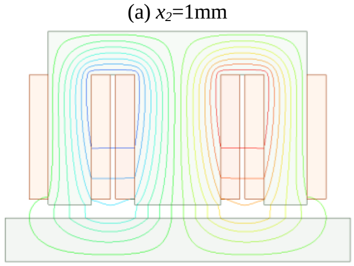
TABLE II. STRUCTURE PARAMETERS OF THE EMS

x_1	Air gap	5 mm
N	Number of coil	250
L	Core thickness	40 mm
i	Coil current	6 A
w_c	Width of E-core center leg	32 mm
h_E	Height of E-core	64 mm

It can be seen from Figure 6 that the magnetic flux leakage and edge effects can be neglected in the case of small air gaps. As the air gap increases, the magnetic flux leakage and edge effects have an increasing influence on the calculation.



(a) x_2=1mm

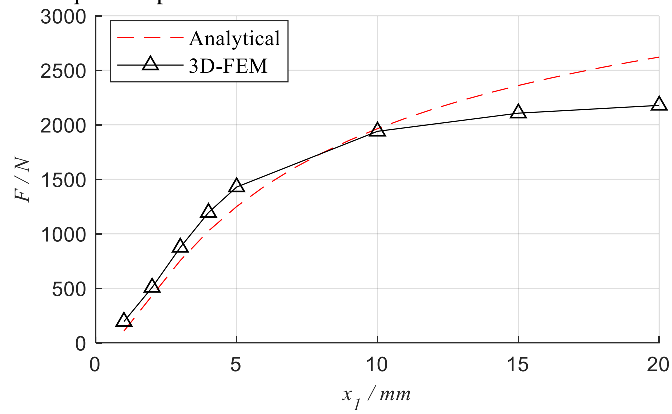


(b) x_2=5mm

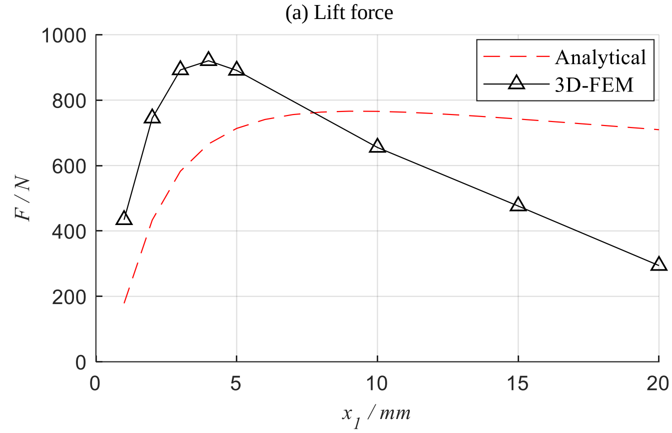
Figure 6. Magnetic field distribution of the EMS at different air gaps in two-dimensional static magnetic field.

IV. RESULTS DISCUSSION

By comparing the analytical results with the simulation, the causes of the errors are analyzed and prepared for the subsequent experiments.



(a) Lift force



(b) Drag force

Figure 7. Lift force and drag force of the PMEDS at different speeds, Solid line is FEM in three-dimensional transient magnetic field, and the dotted line is analytical by formula(3)-(5).

It can be seen from Figure 7 that both of them coincide at low speed, and the simulation is small at high speed due to the aforementioned reasons. The lift force increases with speed and then remains essentially unchanged, while the drag force increases first and then decreases. In practical applications, the train should work in a reasonable speed range to ensure greater lift force and less drag force.

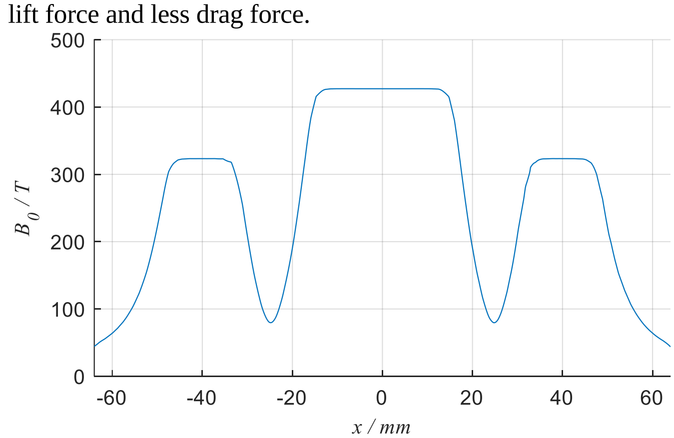


Figure 8. The magnetic flux density in the middle of the air gap when x_2=5 mm.

The magnetic flux density in the middle of the air gap is shown in Figure 8. According to Table 2 and Equation (9), the magnetic flux density at the air gap is 0.377T, which is close to the result in Figure 8, and the magnetic flux density in the core is about 0.833T, which is consistent with the results mentioned above. The magnetic flux density of the center leg is higher than the two sides due to the influence of magnetic flux leakage and edge effects.

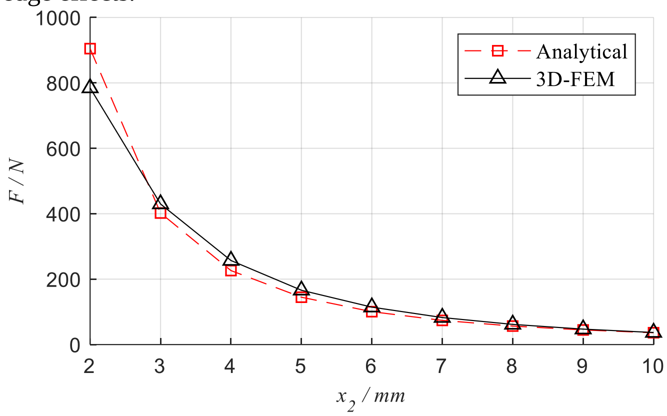


Figure 9. Analytical result and simulation of force-displacement curve.

It can be seen from the curve in Figure 9 that the force-displacement curves obtained by the two methods are consistent and inversely proportional to the square of the air gap. After the air gap is larger than 3mm, the analytical result is smaller than the simulation. The influence of the edge effect on the magnetic pole area is one of the causes of this phenomenon.

V. Conclusions

In this paper, taking vacuum tube maglev transportation as its application background, an EDS&EMS hybrid support is used. Tilt-arranged PMEDS is used to provide the main suspension and guiding force required by the train. Through the analysis and simulation, the relationship between velocity and force is studied. The lift force is gradually increased and the drag force is increased first and then decreased. The lag of eddy current at high speed is the reason why the simulation is less than the analytical result. The electromagnetic suspension is used to improve the stability of the support. As the air gap increases, the edge effect affects the magnetic pole area, resulting in a smaller analytical result, but the magnetic flux density at the air gap is less affected. The analytical method can guide the structural design, and its error with the simulation is small. Next, we will study the influence of structural parameters on the support performance, optimize the parameters, and carry out experimental verification.

References

[1] P. Holmer, "Faster than a speeding bullet train," *IEEE Spectrum*, vol. 40, no. 8, pp. 30–34, 2003.

[2] R. S. Raghunathan, H. D. Kim, and T. Setoguchi, "Aerodynamics of high-speed railway train," *Progress in Aerospace Sciences*, vol. 38, no. 6, pp. 469–514, 2002.

[3] K. Fujii, T. Ogawa, "Aerodynamics of high speed trains passing by each other," *Computers and Fluids*, vol. 24, no. 8, pp. 897–908, 1995.

[4] A. Baron, M. Mossi, and S. Sibilla, "The alleviation of the aerodynamic drag and wave effects of high-speed trains in very long tunnels," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 89, no. 5, pp. 365–401, 2001.

[5] J. Braun, J. Sousa, and C. Pekardan, "Aerodynamic Design and Analysis of the Hyperloop," *Aiaa Journal*, vol. 55, no. 12, pp. 4053–4046, 2017.

[6] H. Kang, Y. Jin, H. Kwon, and K. Kim, "A Study on the Aerodynamic Drag of Transonic Vehicle in Evacuated Tube Using Computational Fluid Dynamics," *International Journal of Aeronautical and Space Sciences*, vol. 18, no. 4, pp. 614–622, 2017.

[7] R. Palacin, "Hyperloop, the Electrification of Mobility, and the Future of Rail Travel [Viewpoint]," *IEEE Electrification Magazine*, vol. 4, no. 3, pp. 4–51, 2016.

[8] R. F. Post, D. D. Ryutov, "The Inductrack: a simpler approach to magnetic levitation," *IEEE Transactions on Applied Superconductivity*, vol. 10, no. 1, pp. 901–904, 2000.

[9] J. Fang, D. B. Montgomery, and L. Roderick, "A Novel MagPipe Pipeline Transportation System Using Linear Motor Drives," *Proceedings of the IEEE*, vol. 97, no. 11, pp. 1848–1855, 2009.

[10] A. Nash, U. Weidmann, S. Buchmueller, and M. Rieder, "Assessing feasibility of transport megaprojects - Swissmetro European market study," *Transportation research record*, no. 1995, pp. 17–26, 2007.

[11] J. Meins, L. Miller, and W. J. Mayer, "The high speed Maglev transport system TRANSRAPID," *IEEE Transactions on Magnetics*, vol. 24, no. 2, pp. 808–811, 1988.

[12] N. Hagele, F. Dignath, "Vertical dynamics of the Maglev vehicle Transrapid," *Multibody System Dynamics*, vol. 21, no. 3, pp. 213–231, 2009.

[13] D. Oster, M. Kumada, and Y. Zhang, "Evacuated tube transport technologies (ET3)tm: a maximum value global transportation network for passengers and cargo," *Journal of Modern Transportation*, vol. 19, no. 1, pp. 42–50, 2011.

[14] R. F. Post, D. D. Ryutov, "The Inductrack Concept: A New Approach to Magnetic Levitation," *Office of Scientific & Technical Information Technical Reports*, 1996.

[15] X. Lyu, Y. Hu, H. Wu, Z. Lin, "Design of High Performance Linear Feedback Laws for Operation That Extends into the Nonlinear Region of Amb Systems," *Control Theory & Technology*, vol. 15, no. 4, 2017, pp. 301-315.