Structural parameters of new rail transit system optimization theory research

Zhifei Wang, Fan Li

Institute of Computing Technology, China Academy of Railway Sciences, Beijing 100081, China

Email: wangfei54188@163.com

Abstract. In response to the defects of maglev system structural parameter design method, the paper puts forward an optimization design based on orthogonal test and computational fluid dynamics, by combining orthogonal theory with fluid mechanics and adopting multi-factor orthogonal test method, the influence trend of tunnel cross section, running speed, pipeline pressure, and on train aerodynamic resistance is studied by taking train aerodynamic resistance as evaluation index, and the sequence of various factors and the influence of different factors on air drag are determined by range and variance analysis, and the optimal parameters are confirmed. The results show that the blocking ratio has the greatest influence on the aerodynamic drag, while the pipeline pressure has the least influence, and the blocking ratio and running speed have the most significant influence on the aerodynamic drag of the train, while the pipeline pressure is not significant. The optimal solutions are for Tunnel cross section, 600km/h for the running speed and 700 Pa for the pipeline pressure. The results of this paper can provide technological interest for the future transportation of the maglev system.

1. Introduction

Currently, wheel-rail type traffic system come to be the main body of rail traffic, the average speed of existing high-speed railway operating circuit reaches up 300km/h, the target speed values of Beijing-Shanghai and Beijing-Tianjin high-speed railway reach up 350km/h. Thus, because the problems at wheel rail action, friction loss and its air resistance, etc, the wheel rail technology difficult to reach up higher speed [1]. The root cause which limits the highest economy speed of ground high speed traffic is the dense air, to get rid of the dense atmosphere’s action, we purpose the vacuum pipeline traffic imagine [2-3]. View in the whole world, the vacuum pipeline high speed traffic still no previous case as sample for reference, but never stop to explore and research, in April, 2017, magnetic suspension trial line “L0 series” train in Yamanashi-ken, Japan realize the highest speed 603km/h, in May, 2016, the U.S.A tested the drive system of Hyperloop pipeline transporting and realize that accelerate to 96km/h within 1s, in 2017, the Southwest JIAOTONG university built the vacuum pipeline high speed ratio model trial line[4-5]. At the pneumatic characteristic research during the running process of vacuum pipeline high speed train, Liu Jiali, Zhang Jiye, Huang Zundi and other people use block ratio, running speed and pipeline pressure as important parameters, and done researched the affect law that three parameters to train’s pneumatic characteristics [6-8]. Wang Haiyang and other people use the environment pressure where train stay, running speed, block ratio, shape of train head and tail, and added the carriage suction system as reference system, analyse the pneumatic characteristics during...
the train running and analyse the energy loss [9-10]. Each factor all had some influence at pneumatic characteristics of train, but still not clear at the influence degree and notable degree of each factor.

This article combines the normal theory and hydrodynamics theory, uses the block ratio, pipeline pressure and train’s running speed as influence factors, adopts multiple factors normal trial method to research the regular of train pneumatic resistance of train, and optimize the trial result, confirm the influence degree and notable degree of each factor to train pneumatic characteristics, obtain the best parameter scheme, provide the theory basis for the research of the vacuum pipeline traffic.

2. Optimize theory

2.1. Normal trial theory

Confirm the normal trial factors. The index of train pneumatic characteristics is air resistance, the main factors which affect the train air resistance are: block ratio, tunnel cross section, running speed and pipeline pressure, According to the level of 3 factor 4, the orthogonal table error of $L_9(3^4)$ is selected as the test indicator, as shown in Table 1.

| Serial No. | Tunnel cross section A | Running speed B(km/h) | Pipeline pressure C(Pa) |
|------------|------------------------|-----------------------|------------------------|
| 1          | $A_1$                  | $B_1$                 | $C_1$                  |
| 2          | $A_1$                  | $B_2$                 | $C_2$                  |
| 3          | $A_1$                  | $B_3$                 | $C_3$                  |
| 4          | $A_2$                  | $B_1$                 | $C_2$                  |
| 5          | $A_2$                  | $B_2$                 | $C_3$                  |
| 6          | $A_2$                  | $B_3$                 | $C_1$                  |
| 7          | $A_3$                  | $B_1$                 | $C_3$                  |
| 8          | $A_3$                  | $B_2$                 | $C_1$                  |
| 9          | $A_3$                  | $B_3$                 | $C_2$                  |

2.2. Calculate hydrodynamics theory

Because the train running speed at $600 \sim 1000$km/h, the corresponding Mach number at $0.49 \sim 0.73$, and the pipeline adopt closed structure and need consider the influence of compressibility of air, so select the ideal air in the trial. Under the general situation, the air around the trail be at complete turbulence status, so, adopt the turbulence model [16] when discussing the numeric simulation of air flowing around the train. The trial adopt standard $k-\varepsilon$ turbulence model, it’s control direction[5-6] as follows:

$$\mu_i = C_\mu \frac{\rho k^2}{\varepsilon}$$

In the formula:

- $\mu_i$ -- Vortex viscosity coefficient.
- $k$ -- Turbulence flow energy.
- $\varepsilon$ -- Turbulence dissipation ratio.
- $C_\mu$ -- For the turbulence constant, under the general situation, select $C_\mu = 0.09$.

Turbulence kinetic energy $k$ equation is:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) \frac{\partial k}{\partial x_j} \right] + \mu \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j} \right) - \rho \varepsilon$$

$$(2)$$
The equation of turbulence dissipation ratio $\varepsilon$ is:

$$
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ (\nu + \frac{\nu_t}{\sigma_{\varepsilon}}) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \frac{\varepsilon}{k} \frac{\partial u_j}{\partial x_j} \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_i}{\partial x_i} \right) - C_2 \frac{\varepsilon^2}{k} \tag{3}
$$

where $\nu$ is ir motion viscosity, $\nu_t$ is the layer flow motion viscosity, $\nu_t$ is turbulence motion viscosity, $C_1$ is experience constant ($C_1 = 1.47$), $C_2$ is experience constant ($C_2 = 1.92$), $\sigma_{\varepsilon}$ is experience constant ($\sigma_{\varepsilon} = 1.33$), $\sigma_k$ is experience constant ($\sigma_k = 1.0$).

3. Construction parameter optimize method

3.1. Hydrodynamics value calculation

Adopt the fluid simulation software fluent to process finite element analysis for the train pneumatic characteristics, the analysis process shown as Figure 1.

![Figure 1. The flow simulation.](image)

Adopt three-dimensional digit modelling software to build train and pipeline model and process Boole calculation. Select the length of train at 100m, height 3.7m and width 3.3m. Limited by the calculation condition and complex train shape, we do suitable simplify at the complex outer structure of train and bottom of train, and smooth handle the train surface. Select the length of pipeline at 500m, the shape at semi round, the transverse section area of pipeline decided by block ratio.

Adopt pre-treatment software ANSYS ICEM process hexahedron structure grid division at the pipeline and surface of train, the max grid size is 500mm, the min grid size is 100mm, the total grid number under different calculation model among $2 \times 10^6$–$5 \times 10^6$, the calculating area shown as the Figure 2.

![Figure 2. Simulation calculation of area.](image)

The exit and entrance all are pressure far field boundary condition, the temperature all are set at 300K, setting pipeline pressure and train speed according to the detail working status, set the trail wall, pipeline ground and pipeline wall as fixed wall, means that no relative sliding with the air, the pipeline, train wall and ground all adopt standard wall function simulation. The calculating result shown as Figure 3.
3.2. Normal trial parameter optimization

The trial selects three factors, namely pipeline pressure, running speed, and pipeline section, each factor has three levels, as shown in Table 2.

| Table 2. Factor levels for orthogonal test of Structural Parameters Optimization. |
|-------------------------------------------------------------|
| Factor                        | Level 1 | Level 2 | Level 3 |
|--------------------------------|---------|---------|---------|
| Tunnel cross section A         | 1-Semicircle | 2-Square | 3-Circular |
| Running speed B(km/h)          | 700     | 800     | 900     |
| Pipeline pressure C(Pa)        | 700     | 800     | 900     |

The trial adopts $L_{16}(4^3)$ normal table, each trial value all adopts FLUENT to process simulation calculation, then get out the trial result shown as Table 3.

| Table 3. Experimental results for orthogonal test. |
|--------------------------------------------------|
| Serial No. | Tunnel cross section A | Running speed B(km/h) | Pipeline pressure C(Pa) | Air drag Y (N) |
| 1          | 1                      | 600                   | 600                    | 2039.78       |
| 2          | 1                      | 800                   | 700                    | 4593.98       |
| 3          | 1                      | 1000                  | 800                    | 2335.55       |
| 4          | 2                      | 600                   | 700                    | 1781.51       |
| 5          | 2                      | 800                   | 800                    | 4389.96       |
| 6          | 2                      | 1000                  | 600                    | 5967.55       |
| 7          | 3                      | 600                   | 800                    | 1970.36       |
| 8          | 3                      | 800                   | 600                    | 3753.52       |
| 9          | 3                      | 1000                  | 700                    | 7627.17       |

Contrast 9-time trial in the normal Table 3, then find that, the pneumatic resistance in No.4 trial is the minimum in 9 times trial. For the resistance index of train, more small pneumatic resistance better then get that A2B1C2 is the best scheme in the 9 types schemes.

4. Data analyses

4.1. Trial result analyses
Utilize the simulation software FLUENT to research the pneumatic characteristics of low vacuum pipeline high-speed train, the simulation result shown as Figure 4.

From the Figure 4 we can know, the block ratio of train and pipeline not change, when the pipeline pressure of the train is any pressure among 700~1000pa, the pneumatic resistance of train increasing along with the increase of train’s running speed, for the same one running speed, the pneumatic resistance of train increasing along with increase of pipeline pressure. The train running speed not change and when the pipeline pressure of the train is any pressure among 700~1000pa, the pneumatic resistance of train increasing along with the increase of block ratio. So, reducing the pipeline pressure or expanding the section area of the pipeline all can reach up the purpose of reduce resistance, but can’t seeking the resistance reduce effect then expand the pipeline’s section area, also should considering its economic efficiency.

4.2. The range analyses of trial data
Judge the primary and secondary of factors through the size of range, and explored the best scheme. The trial only has one index, needn’t consider the mutual action, so select the better trial scheme only need consider the size of the index value of each factor’s different horizontal trial result. Firstly calculate the index sum of different horizontal and error, means T1, T2 and T3. Then calculate the range of three horizontal trial result of each factor, the calculation formula [11] as below.

\[
\begin{align*}
T_{A1} &= \frac{(Y_1 + Y_2 + Y_3)}{3} \\
T_{A2} &= \frac{(Y_4 + Y_5 + Y_6)}{3} \\
T_{A3} &= \frac{(Y_7 + Y_8 + Y_9)}{3}
\end{align*}
\]  

Figure 4. Comparison of simulation results.
According to the formula (4) to (7) to calculate the different levels of the indicators and the results as shown in Table 4.

\[
\begin{align*}
T_{B1} &= (Y_1 + Y_4 + Y_7)/3 \\
T_{B2} &= (Y_2 + Y_5 + Y_8)/3 \\
T_{B3} &= (Y_3 + Y_6 + Y_9)/3 \\
T_{C1} &= (Y_1 + Y_6 + Y_8)/3 \\
T_{C2} &= (Y_2 + Y_4 + Y_6)/3 \\
T_{C3} &= (Y_3 + Y_5 + Y_7)/3 \\
R &= T_{MAX} - T_{MIN}
\end{align*}
\]

Table 4. Extremum difference analyses for Experimental results.

| Serial No. | Tunnel cross section B | Running speed C(km/h) | Pipeline pressure D(Pa) | Air drag Y (N) |
|------------|------------------------|------------------------|------------------------|---------------|
| T1         | 8969.31                | 5791.65                | 11760.85              | SUM = 34459.38 |
| T2         | 12139.02              | 12737.46              | 14002.66              | MEAN = 3828.82 |
| T3         | 13351.05              | 15930.27              | 8695.87               |               |
| R          | 8969.31                | 5791.65                | 11760.85              |               |

Figure 5. Effects of new rail transit system parameter levels on air drag.

From Table 4 and Figure 5, the optimum condition of design parameters is A2B1C2 and the optimum values of the parameters for minimizing air drag condition are given as follows: \( A2=2 \), \( B1=600 \text{km/h} \), and \( C2=700 \text{Pa} \).

5. Conclusion
1) When the block ratio and speed keep unchanged, the pneumatic resistance of train also increasing along with the increase of the pipeline pressure. When the block ratio and pipeline pressure not change, the pneumatic resistance of train also increasing along with the increase of the running speed. So can
reduce the pipeline pressure or expand the pipeline transverse section under the situation that considered the economy.

2) the optimum condition of design parameters were A2B1C2 and the optimum values of the parameters for minimizing air drag condition were given as follows: A2=2, B1=600km/h, and C2=700Pa.

Acknowledgments
This work was financially supported by the Science and technology research program of China Railway (J2019X005), the Science and technology research program of China Railway Network Business Co. Ltd (DFYF19-12/13), and Foundation of China Academy of Railway Sciences(1951DZ1503).

References
[1] Deng Zigang, Li Haitao 2017 Recent Development of High-Temperature Superconducting Maglev[J] Materials China 36(5) 329-333
[2] Zhou Qingyue, Liu Fengshou, Zhang Yinhua, etc. Solutions for Problems at Wheel-Rail Interface in High Speed Railway[J] China Railway 2017 Science 38(5) 78-84
[3] Chen Xuyong, Zhao Lifeng, Ma Jiaqing, etc. 2013 Dynamics Simulation of Rescuing of Magnetic-Levitation Train Running in Evacuated Tube[J] Chinese Journal of Vacuum Science and Technology 33(11) 1100-1104
[4] Shen Zhiyun 2005 On Developing High-Speed Evacuated Tube Transportation in China[J] Journal of Southwest Jiaotong University 40(2) 133-137
[5] Jin Maojing, Huang Ling 2017 Development Status and Trend of Ultra-high Speed Vacuum Pipeline Transportation Technology [J] Science and technology of China (3) 13-15
[6] Liu Jiali , Zhang Jiye , Zhang Weihua 2013 Analysis of Aerodynamic Characteristics of High-speed Trains in the Evacuated Tube[J] Journal of Mechanical Engineering 49(22) 137-143
[7] Liu Jiali , Zhang Jiye, Zhang Weihua 2019 Impacts of Pressure, Blockage-Ratio and Speed on Aerodynamic Drag-Force of High-Speed Trains[J] Chinese Journal of Vacuum Science and Technology 55(8) 166-143
[8] Huang Zundi, Liang Xifeng, Chang Ning 2018 Numerical Analysis of Train Aerodynamic Drag of Vacuum Tube Traffi c Journal of Mechanical Engineering 55(8) 165-172
[9] Wang Haiyang 2018 Analysis of Aerodynamic Characteristics and Energy Consumption of ETT system at High Speed Operation[D] Changsha: Hunan University
[10] Zhou Xiao, Zhang Diaoye, Zhang Yaoping 2008 Numerical Simulation of Blockage Rate and Aerodynamic Drag of High-Speed Train in Evacuated Tube Transportation[J] Chinese Journal of Vacuum Science and Technology 28(6) 535-538
[11] Fang Kaitai, Ma Changxing 2001 Orthogonal and uniform test design [M] Beijing: Science Press
[12] Wang Zhifei, Wang Hua 2012 Inflatable Wing Design Parameter Optimization Using Orthogonal Testing and Support Vector Machines [J] Chinese Journal of Aeronautics 25(6) 887-895
[13] Wu Yifei, Zhao Hongxia, Zhang Cunquan, et al. 2018 Optimization Analysis of Structure Parameters of Steam Ejector Based on CFD and Orthogonal Test [J] Energy (151) 79-93
[14] Sun Yang, Tang Dunbing, Yang Jun, etc. 2017 Numerical Investigation of Motor Frame Based on Orthogonal Experimental Method[J] Mechanical manufacture and Automation Major (6) 100-103
[15] Wang Xiaozeng, Yang Jiuhong 2014 Hydraulic Cylinder Boring Quality Range Analysis Based on Orthogonal Test [J] Advanced Materials Research 945-949 1289-1292
[16] Yan Chao 2006 Computational Fluid Dynamics [M] Beijing: Beihang University Press