Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 11.14
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.11.14

Sensitivity Analysis and Optimization of Weighting Coefficients in MPC for 600 km/h High-Speed Maglev Levitation System

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Abstract

The pursuit of sustainable high-speed mobility has positioned magnetic levitation (Maglev) technology, particularly the 600 km/h generation developed by CRRC Qingdao Sifang, at the forefront of modern transportation research. Ensuring stable levitation at such extreme velocities requires control strategies capable of handling severe nonlinearities and stringent safety constraints. Building upon the Model Predictive Control framework previously developed at the Institute of Engineering and Computational Mechanics (ITM), University of Stuttgart, the critical influence of cost function weighting coefficients on the closed-loop performance of the electromagnetic levitation is investigated. While MPC offers superior tracking capabilities compared to classical control schemes, the optimal balance between air-gap precision and ride comfort remains a complex engineering challenge under track irregularities. A systematic sensitivity analysis is conducted through a series of comprehensive numerical simulations, spanning a grid of weighting coefficients for air-gap deviation, magnet current, and acceleration. By leveraging a vehicle-guideway coupled model that accounts for nonlinear dynamics, the inherent trade-off between tracking stiffness and vibration isolation is quantitatively evaluated, providing a robust framework for optimizing the control performance of the electromagnetic levitation system. These findings contribute to the refinement of existing distributed MPC architectures, ensuring both safety margins and operational efficiency for the next generation of high-speed Maglev transit.

Keywords: high-speed maglev, model predictive control, parameter optimisation, magnetic levitation, sensitivity analysis, weighting coefficients optimization.

1 Introduction

The demand for efficient and sustainable transportation has propelled significant advancements in high-speed magnetic levitation (Maglev) technology. As a landmark innovation, the development of Maglev vehicles by CRRC Qingdao Sifang, capable of reaching speeds of 600 km/h, underscores the critical need for robust control systems that ensure stable levitation and ride comfort under extreme operational conditions [1]. Achieving such ultra-high speeds introduces complex engineering challenges, primarily maintaining the stability of the electromagnetic levitation system while contending with inherent nonlinear dynamics and external disturbances, such as track irregularities and elastic guideway deflections [10]. Recent progress in control engineering has shifted the focus from traditional linear methods to more sophisticated strategies, notably Model Predictive Control (MPC) [2, 3]. By anticipating future system behavior and optimizing control inputs over a defined horizon, MPC offers superior closed-loop performance in handling the nonlinear coupling of the levitation process [4, 6]. However, the effectiveness of MPC is highly sensitive to the configuration of its cost function weighting coefficients [8]. Variations in the balance between air-gap deviation, electromagnetic acceleration, and coil current can significantly alter control performance, potentially leading to increased vibrations or degraded stability at high speeds [5, 9]. Despite its importance, a comprehensive understanding of how these weighting profiles influence the system's dynamic response under extreme velocity remains insufficient. This study addresses these challenges by conducting a systematic sensitivity analysis across a multi-dimensional grid of MPC weighting coefficients, quantitatively evaluating the trade-offs between air-gap precision, ride comfort, and actuator stability under realistic 600 km/h operational disturbances. By providing critical insights into optimal MPC parameter-tuning strategies, this work contributes to the refinement of control architectures for next-generation high-speed Maglev transit, thereby enhancing operational reliability and ensuring safe, comfortable performance at the frontiers of terrestrial speed.

2 System Methodology and Control Strategy Implementation

The fundamental configuration and dynamic modelling of the electromagnetic levitation system are illustrated in Figure 1. The system relies on an onboard electromagnet to generate an attractive force (F_{mag}) that counteracts gravity, maintaining a stable air gap (s) through a highly nonlinear and inherently unstable electromagnetic-mechanical coupling. To stabilize this process, Model Predictive Control (MPC) is implemented, which operates based on a "predictive-corrective" mechanism rather than simple reactive feedback [6].

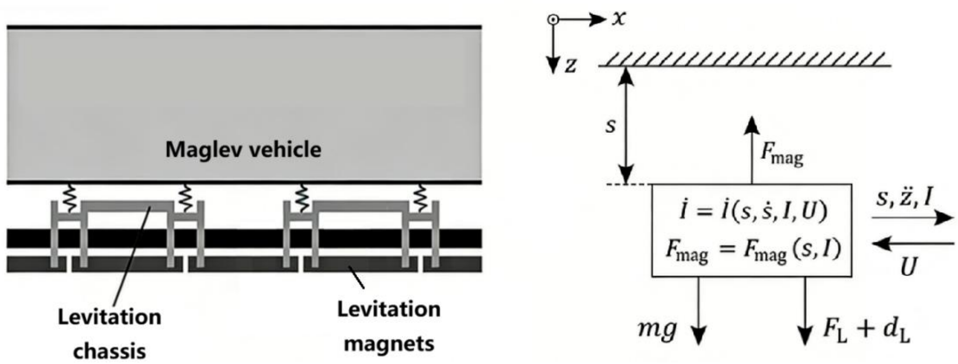

Figure 1: Physical structure and dynamic model of the levitation system [8].

Specifically, the MPC algorithm functions through three core stages:

a) Predictive Modelling: At each sampling instant τ, the controller utilizes the internal nonlinear dynamic model to simulate the future trajectories of the state variables (air gap s, vertical acceleration $\ddot{z}$, and current I) over a finite prediction horizon (T_p). The model accounts for the balance between the electromagnetic force (F_{mag}) and the external loads, which consist of the static load (F_L) from the vehicle body and dynamic disturbances (d_L) such as aerodynamic forces. This allows the system to "foresee" the impact of current control actions and track irregularities before they fully manifest [2, 10].
b) Rolling Optimization: Within this horizon, the controller solves an open-loop optimal control problem in real-time. It seeks a sequence of control inputs (voltage U) that minimizes a multi-objective cost function J, subject to physical constraints such as voltage saturation and current limits. This optimization process ensures an optimal balance between levitation precision and motion smoothness [6, 8].
c) Receding Horizon Execution: Although an entire sequence of future control moves is calculated, only the first element of this sequence is applied to the actuator. In the next sampling step, the entire process is repeated with updated sensor measurements (air-gap, acceleration feedback and current), providing a receding horizon strategy that inherently compensates for model mismatches and external disturbances [2, 6].

Based on this iterative logic, the optimal control law is derived by minimizing the following cost function J:

$$J = \int_t^{t+T_p} \left(Q_s\left(s(\tau) - s_{ref}\right)^2 + Q_{\ddot{z}}\ddot{z}(\tau)^2 + Q_I\left(I(\tau) - I_{ref}\right)^2 + RU(\tau)^2 \right) d\tau \tag{1}$$

T_p denotes the prediction horizon. The state variables include the air-gap deviation $s(\tau)$, the vertical electromagnetic acceleration $\ddot{z}(\tau)$, and the coil current $I(\tau)$, while $U(\tau)$ represents the control voltage applied to the magnets. The terms s_{ref} and I_{ref} denote the nominal air-gap and the rated equilibrium current, which serve as the reference targets for the controller. The optimization process is guided by the weighting matrix $Q = diag(Q_s, Q_{\ddot{z}}, Q_I)$, which balances the trade-offs between levitation precision, motion smoothness, and control stability [2, 6]. Specifically, a higher weight assigned to the air-gap deviation (Q_s) ensures stringent tracking of the reference position to prevent physical contact with the guideway [8, 10]. The inclusion of electromagnetic acceleration ($Q_{\ddot{z}}$) as a penalized variable aims to suppress high-frequency oscillations and enhance the system's damping characteristics [9]. Furthermore, the coil current weight (Q_I) is included to regulate energy consumption and stabilize actuator dynamics. The control weight R is primarily selected to ensure the numerical feasibility of the optimization and to prevent actuator saturation, and its value remains fixed throughout the sensitivity analysis [4, 7].

The theoretical performance of the electromagnetic levitation system is intrinsically linked to the configuration of the weighting coefficients within the MPC cost function, as these parameters dictate the prioritization of competing control objectives [8]. Specifically, the weighting coefficient assigned to the air-gap deviation directly governs the static and dynamic tracking precision; a higher penalty on this term enforces a rigid adherence to the nominal equilibrium, which is essential for preventing physical contact with the track but may lead to increased control effort [2]. Conversely, the coefficient for electromagnetic acceleration serves as a primary regulator for system smoothness and passenger comfort [9]. By penalizing rapid changes in acceleration, the controller is theoretically guided to suppress high-frequency vibrations and mitigate the "overshoot" common in nonlinear electromagnetic systems [2]. In this study, the inclusion of the current weight (Q_I) represents a strategic balancing act; it ensures that the voltage-based control law maintains mechanical stability and damping while preventing excessive current fluctuations that could destabilize the power electronics [4]. The theoretical interaction between these weights—balancing the necessity of gap precision against the requirements for smooth acceleration and actuator stability—forms the basis for the subsequent performance evaluation [3, 4, 11]. Consequently, the following simulation analysis is conducted to quantitatively investigate how varying these weighting profiles influences the system's robustness and response characteristics under dynamic operational conditions.

3 Sensitivity Analysis of Weighting Coefficients

To systematically evaluate the influence of the air-gap deviation (Q_S), magnet acceleration ($Q_{\ddot{z}}$), and coil current (Q_I) on the overall control quality, a comprehensive sensitivity analysis is conducted. The simulations are performed using the TR.Mechatron platform, which employs a lateral vehicle cross-section model. This model integrates a pair of levitation and guidance units, accounting for the nonlinear electromagnetic forces and the dynamic coupling between the magnets and the flexible guideway [11]. The primary objective is to quantify the inherent trade-offs between tracking precision, vibration isolation, and control effort. The system is tested under a demanding scenario at a vehicle speed of 600 km/h. In this study, the track irregularity serves as the sole source of excitation, specifically modelled after the theoretical deflection of a Euler-Bernoulli beam to represent typical guideway sag. No additional stochastic elements or external disturbances are introduced, allowing for a focused analysis of the system's response to structural track deformations. During the simulation, the air-gap, acceleration, and current are recorded. The absolute displacement of the magnets $z(\tau)$ is subsequently determined by the kinematic relationship $z(\tau)= s(\tau) + g_z(\tau)$, where $s(\tau)$ is the recorded air-gap and $g_z(\tau)$ is the instantaneous guideway irregularity in the vertical direction. This approach ensures an accurate evaluation of the spatial trajectory of levitation magnets relative to the inertial reference frame.

The sensitivity analysis evaluates the influence of the weighting coefficients (Q_s, $Q_{\ddot{z}}$, Q_I) on control quality through a prioritized investigation. The analysis first prioritizes the air-gap weight (Q_s) to establish fundamental tracking stiffness, followed by the evaluation of the acceleration weight ($Q_{\ddot{z}}$) for damping and ride comfort, and finally the current weight (Q_I) for control stability. This tiered approach facilitates the identification of an optimal weighting configuration that ensures robust levitation under dynamic track disturbances at extreme speeds.

3.1. Sensitivity Analysis of Air-Gap Weighting coefficient

Case I focuses on the air-gap weight (Q_s), which is theoretically the most critical parameter for maintaining levitation stability and ensuring tracking accuracy. With the acceleration weight ($Q_{\ddot{z}}$) and current weight (Q_I) both fixed at 1, Q_s is varied across a spectrum of $Q_s \in [2, 10, 100, 200]$.

The simulation results shown in Figure 2 demonstrate that the system performance is highly sensitive to the magnitude of Q_s. A low weight (e.g., $Q_s = 2$ or $Q_s = 10$) leads to insufficient magnetic stiffness, resulting in sluggish tracking of the guideway profile and significant peak-to-peak air-gap deviations. Conversely, excessively high weights (e.g., $Q_s = 200$) cause the controller to over-penalize minor gap errors, inducing high-frequency oscillations that eventually lead to system divergence.

The configuration of 100-1-1 is identified as the optimal balance. Under this parameter set, both the air-gap fluctuation and the magnet displacement range (maximum to minimum) are significantly lower than those in other combinations. The response curves exhibit superior smoothness, and the system operates with enhanced stability. Notably, while the air-gap and displacement metrics show substantial improvement, the coil current fluctuations do not exhibit a distinct difference across the various Q_s settings in this group. This suggests that within the stable range of Q_s, the current effort is primarily dictated by the fundamental levitation force required to counteract the rail geometry rather than the gap-specific penalty.

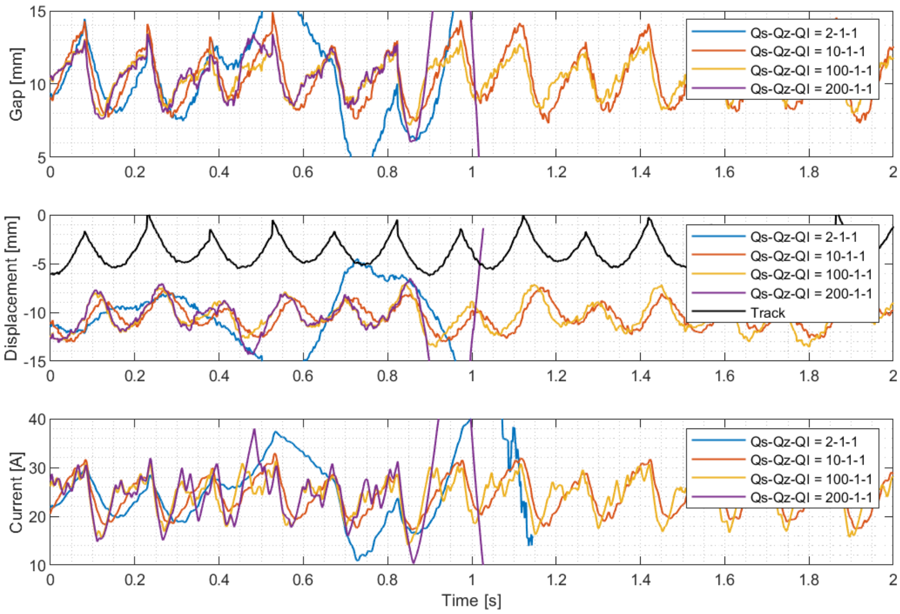

Figure 2. Air-gap, magnet displacement vs. track, and current for varying Q_S.

3.2. Sensitivity Analysis of Acceleration Weighting coefficient

Case II focuses on the acceleration weight ($Q_{\ddot{z}}$), which is instrumental in enhancing the ride comfort and damping characteristics of the suspension system. Building upon the optimal air-gap weight ($Q_S = 100$) identified in Case I, and maintaining the current weight (Q_I) at 1, $Q_{\ddot{z}}$ is varied from 1 to 100 to observe its impact on the dynamic response.

The simulation results shown in Figure 3 demonstrate that increasing $Q_{\ddot{z}}$ effectively suppresses the vertical vibration of the electromagnet. Under the optimal acceleration weight of 5 (forming the 100-5-1 combination), the system achieves significantly lower air-gap fluctuations and magnet displacement ranges compared to other weight sets. The resulting response curves are visibly smoother, and the overall operation is more stable, demonstrating superior vibration isolation performance. The acceleration weight must be selected within a reasonable range. An excessively large $Q_{\ddot{z}}$ leads to a "sluggish" response to track irregularities, as the controller prioritizes minimizing acceleration over maintaining the gap, eventually causing the system to lose control and diverge. Similar to the observations in Case I, the coil current fluctuations show no significant variation across the different stable $Q_{\ddot{z}}$ settings, indicating that the current effort remains primarily consistent as long as the system remains within its stable operating envelope.

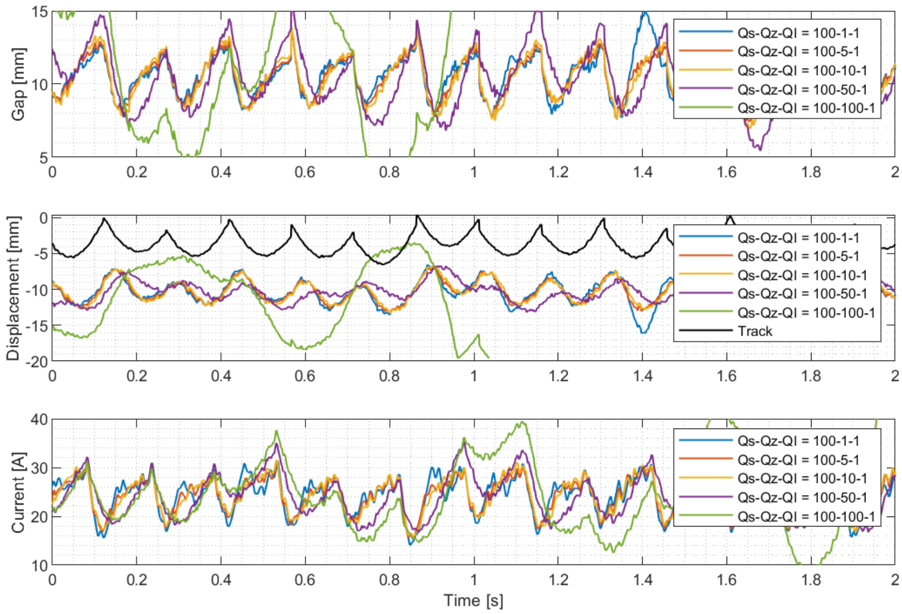

Figure 3. Air-gap, magnet displacement vs. track, and current for varying $Q_{\ddot{z}}$.

3.3. Sensitivity Analysis of Current Weighting coefficient

Case III examines the necessity of the current weight (Q_I) for control stability and actuator protection. Utilizing the previously optimized values ($Q_s = 100$ and $Q_{\ddot{z}} = 5$), Q_I is adjusted from 1 to 50 to investigate its influence on the control effort and system robustness.

The simulation results shown in Figure 4 demonstrate that when Q_I is too small, the coil current exhibits significant high-frequency fluctuations at a fixed frequency. This chattering phenomenon not only degrades the overall control performance but also poses a potential risk of damaging the power electronics and introducing electromagnetic noise into the system. Increasing Q_I to 10 effectively stabilizes these current fluctuations, smoothing the control effort without compromising tracking precision.

However, a further increase in Q_I beyond a certain threshold leads to system instability. An excessively large current weight overly restricts the control authority, preventing the electromagnet from generating sufficient force to counteract dynamic loads and track irregularities. This limitation results in a failure to maintain the nominal air-gap. Consequently, the weighting profile of 100-5-10 is identified as the optimum, providing the best trade-off between tracking accuracy, ride comfort, and electrical stability for the electromagnetic suspension system.

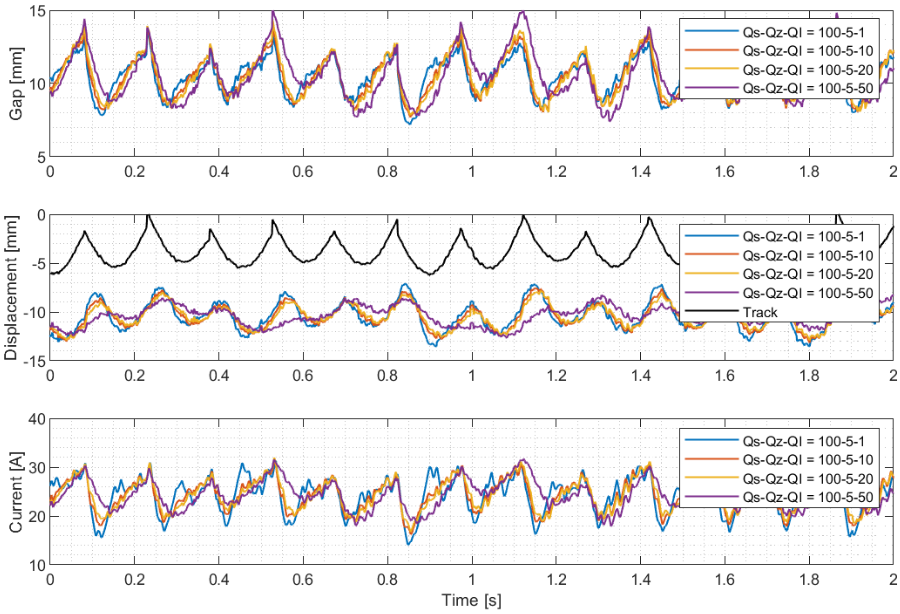

Figure 4. Air-gap, magnet displacement vs. track, and current for varying Q_I.

3.4. Summary of Performance Metrics

To quantitatively evaluate the control performance under different weighting profiles, several statistical metrics are employed. In addition to the fundamental maximum, minimum, and peak-to-peak (range) values, which define the operational boundaries and safety margins of the air gap, two higher-order metrics are introduced:

a) Standard Deviation (Std): Utilized as the primary indicator of control stability. A lower Std in the air-gap deviation signifies a more consistent levitation state with minimal stochastic fluctuations.

b) Root Mean Square (RMS) of Acceleration: Employed as a standard proxy for vibration isolation performance and ride comfort.

The experimental results, as summarized in Table 1, reveal a clear trade-off between tracking precision and motion smoothness. Increasing the air-gap weight (Q_s) from 10 to 100 significantly reduces the Gap Std from 1.8 to 1.4, though at the slight expense of increased acceleration. Conversely, excessively high values of the acceleration weight ($Q_{\ddot{z}}$), such as 50, lead to a dramatic expansion of the gap range (13.3 mm), which may compromise levitation safety.

Comprehensive analysis confirms that the weighting profile (100-5-10) represents the optimal balance. Under this configuration, the system achieves a superior Gap Std of 1.4 mm and a balanced Acceleration RMS of 1.1g, while maintaining a stable current Std of 3.4. Compared to other combinations, this profile consistently minimizes the gap difference (8.0 mm) and ensures the air gap remains well within the safe operational window (6.3 mm to 14.3 mm). This quantitative evidence validates that the 100-5-10 configuration effectively harmonizes the competing objectives of tracking precision, vibration suppression, and electrical reliability, ensuring both safety and comfort for the 600 km/h Maglev system.

Q_s-$Q_{\ddot{z}}$-Q_I	Gap min [mm]	Gap max [mm]	Gap range [mm]	Gap Std	Acceleration RMS	Current Std	Status
2-1-1	NaN	NaN	NaN	NaN	NaN	NaN	unstable
10-1-1	5.9	15.3	9.4	1.8	1.0	3.9	stable
100-1-1	5.6	15.2	9.6	1.4	1.1	4.1	stable
200-1-1	NaN	NaN	NaN	NaN	NaN	NaN	unstable
500-1-1	NaN	NaN	NaN	NaN	NaN	NaN	unstable
100-5-1	6.3	13.9	7.6	1.4	1.1	3.5	stable
100-10-1	5.9	14.3	8.4	1.6	1.1	3.7	stable
100-50-1	4.5	17.8	13.3	2.0	1.0	4.1	Stable (oscillatory)
100-100-1	NaN	NaN	NaN	NaN	NaN	NaN	unstable
100-5-10	6.3	14.3	8.0	1.4	1.1	3.4	stable
100-5-20	6.5	14.7	8.1	1.5	1.0	3.2	stable
100-5-50	6.5	16.7	10.2	1.9	1.0	3.5	stable (conservative)

Table 1: Statistical Performance Metrics for Different Weighting Combinations.

4 Conclusions and Contributions

Sensitivity analysis at 600 km/h indicates that enhancing tracking stiffness against Euler-Bernoulli beam deflections requires an increased air-gap weight. Simultaneously, the acceleration and current weights must be optimized to mitigate high-frequency vibrations, ensuring stability. The identified optimal weighting configuration ensures robust and stable levitation performance even under severe guideway sag at extreme speeds, providing a systematic methodology and a valuable reference for the controller design and parameter tuning of next-generation ultra-high-speed maglev transportation systems.

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