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An adaptive vibration control method to suppress the vibration of the maglev train caused by track irregularities

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ABSTRACT

The levitation gap of the urban maglev train is around 8 mm, which puts a rather high requirement on the smoothness of the track. In practice, it is found that the track irregularity may cause stability problems when the maglev train is traveling. In this paper, the dynamic response of the levitation module, which is the basic levitation structure of the urban maglev train, is investigated in the presence of track irregularities. Analyses show that due to the structural configuration of the levitation module, the vibration of the levitation gap may be amplified and "resonances" may be observed under some specified track wavelengths and train speeds; besides, it is found that the gap vibration of the rear levitation unit in a levitation module is more significant than that of the front levitation unit, which agrees well with practice. To suppress the vibration of the rear levitation gap, an adaptive vibration control method is proposed, which utilizes the information of the front levitation unit as a reference. A pair of mirror FIR (finite impulse response) filters are designed and tuned by an adaptive mechanism, and they produce a compensation signal for the rear levitation controller to cancel the disturbance brought by the track irregularity. Simulations under some typical track conditions, including the sinusoidal track profile, random track irregularity, as well as track steps, indicate that the adaptive vibration control scheme can significantly reduce the amplitude of the rear gap vibration, which provides a method to improve the stability and ride comfort of the maglev train.

1. Introduction

The maglev train technology has gained firm progress in the past two decades, and worldwide interests on the research of maglev train lead to success operations of several commercial maglev lines in China, Japan, and Korea. However, for the urban maglev train, the levitation gap between the electromagnets and the track is around 8 mm, which puts a strict requirement on the smoothness of the track profile since the unevenness of the track causes the levitation gaps to vibrate while the train is traveling. The vibration of the levitation gap not only reduces the ride quality of the maglev train, but also may lead to crash between the electromagnets and the track if the amplitude of the vibration exceeds a certain value. It is observed that once the vertical vibration velocity of the electromagnet exceeds 0.1 m/s when the train is traveling, the electromagnet may crash with the track – because under such a circumstance, the slew rate of the current through the electromagnet cannot reach the requirement to stabilize the system. Once the electromagnets crashes the track when the

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Nomenclature

A	area of the magnetic pole
$\bar{\mathbf{A}}$	7 × 7 state space matrix
A_0	amplitude of the sinusoidal track irregularity
$\mathbf{A_G}$	6 × 6 state space matrix
$\mathbf{A_T}$	7 × 7 state space matrix
$\bar{\mathbf{B}}$	7 × 1 complex column vector
$\mathbf{B_G}$	6 × 1 column vector
$\mathbf{B_T}$	7 × 1 column vector
$\bar{\mathbf{C}}_1$	1 × 7 complex column vector
$\mathbf{C_G}$	1 × 6 column vector
$\mathbf{C_T}$	1 × 7 column vector
d	input of the rear levitation controller
e_2	rear levitation gap error
F_1	front electromagnetic force
F_2	rear electromagnetic force
g	acceleration due to gravity
$G(s)$	transfer function of the path from y_f to y_{12}
i_0	steady state levitation current
i_1	current through the front coil pair
i_2	current through the rear coil pair
i_{e1}	desired front levitation current
i_{e2}	desired front levitation current
$\mathbf{I}_{7\times7}$	7 × 7 identity matrix
j	$\sqrt{-1}$
J	moment of inertia of the levitation module
J_0	performance index
k_a	acceleration feedback coefficient
k_c	proportional coefficient of the current loop
k_d	differential coefficient of the PD controller
k_p	proportional coefficient of the PD controller
l	length of an electromagnet coil
m_1	equivalent mass of the electromagnet
N	number of turns of a single coil
r	input of the state space model
R_0	DC resistance of the coil
s	the *Laplace* operator
S_1	measured front levitation gap
S_2	measured rear levitation gap
$\bar{S}_1$	average front levitation gap
$\bar{S}_2$	average rear levitation gap
$S(x)$	air gap along x axis
$T(s)$	transfer function of the path from d to y_{12}
u_1	control voltage of the front levitation unit
u_2	control voltage of the rear levitation unit
v	train speed
$\mathbf{W}$	weight vector of the FIR filter
$\mathbf{X}$	state vector
$\mathbf{X}'$	state vector of the right FIR filter
y_{0x}	displacement of the track
y_{11}	displacement of the front levitation unit
y_{12}	displacement of the rear levitation unit
y_{1m}	displacement of the electromagnet in the middle
y_f	feed-forward signal
z_0	expected levitation gap in steady state
φ_0	initial phase of the sinusoidal track irregularity
λ	spatial wavelength of the track
θ	pitch angle of the electromagnet
μ	convergence constant
μ_0	the space permeability
ω	frequency
∇	gradient of J_0

train is running, instability problem may occur and passengers may panic due to the heavy clang, which is totally unacceptable for the maglev system. On the other hand, the cost of the maglev guideway takes up 60–80% of the initial capital [1,2], hence the tolerance of the levitation system to track irregularities indirectly determines the costs of the track manufacture and maintenance. Moreover, increasing the speed of the urban maglev train to 160–200 km/h may be a trend in the next decade, thus the dynamic problem of the urban maglev vehicle under track irregularities would become an important subject to be studied.

The vibration problem of the moving maglev train subjected to track irregularities is one of the maglev vehicle-guideway interaction problems which have gained lot of attentions ever since the first maglev test line was constructed. As discussed in [3], the maglev vehicle-guideway interaction problems include: the vibration problem between a moving maglev train and flexible girders; the self-excited vibration when the maglev train is suspending above a girder without moving; and the vibration induced by track irregularities when a maglev train is traveling. The first two problems are mainly induced by the flexibilities of the girders, and they are not concerned in this study. For the third problem which is concerned in this study, three main aspects need to be considered when investigating the maglev vehicle-guideway interaction problem: the guideway model, the maglev vehicle model, and the levitation control system.

For the guideway model, the vertical track irregularities are mainly concerned. Generally, track irregularities can be caused by track surface roughness, misalignment of adjacent track segments, construction tolerance, pier elevation differences, support settlement, etc. [4,5] As a simple and special case, periodical track irregularity may exist as a result of the bending of continuous elevated girders. For example, the bending of elevated girders was treated as a periodical irregularity and was investigated in [6]. The sinusoidal profile has been employed as the track profile in some literature as well [7,8]. Although simple, this model is suitable to study the resonance problem of the maglev train under specific periodical irregularities. However, in more general cases, the track random irregularity needs to be taken into account. In some research where field data of a real maglev line is unavailable, the random track irregularity can be obtained by empirical fittings of current railway data. This can be done either by discrete frequency approach, or by PSD (power spectral density) approach [9,10]. In these approaches, the track surface is described by a power spectral density, and then vertical track geometry can