Design of EMS-Magnetically Levitated System based on Genetic Algorithm

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Abstract

The primary objective of the electromagnetic suspension system is to provide stable suspension under all operating conditions. The actuator that provides the basic suspension force is an electromagnet; its design is influenced by the dynamic considerations (stability, riding comfort, etc), as well as static characteristics, e.g. power requirement and power loss in the magnet, weight of the magnet and the configuration of the magnet-guideway. In addition, the electromagnet should be capable of providing an adequate margin of safety without excessive increase in magnet weight/power input.

Then, in this paper, in order to achieve design optimization of the electromagnetic suspension system (EMS) for magnetically levitated vehicle on its dynamic performance and weight, a design scheme based on genetic algorithm is proposed. The optimum system parameters are searched by GA. Better coordination between component design and vehicle dynamics is obtained on the HSST-type system operating in the medium velocity around 200km/h.

1 Introduction

As a new urban transportation system, magnetically levitated system of low- or medium-speed has been developed. This magnetic levitation technology can be expected that excellent characteristics can be realized in comparison with the conventional railway system, for instance, rapidity, degree of freedom of route selection, friendly environmental, low-maintainability, etc. The High Speed Surface Transport system (HSST) is one of the systems that realize these characteristics, and the world's first business line will start in Eastern Hillside Line of Aichi Prefecture from 2005. Though the running test up to 100 [km/h] has been completed, it is required to achieve higher speed and economical systems when a wider application in the future, for instance, between cities and airport commutation, etc. are considered.

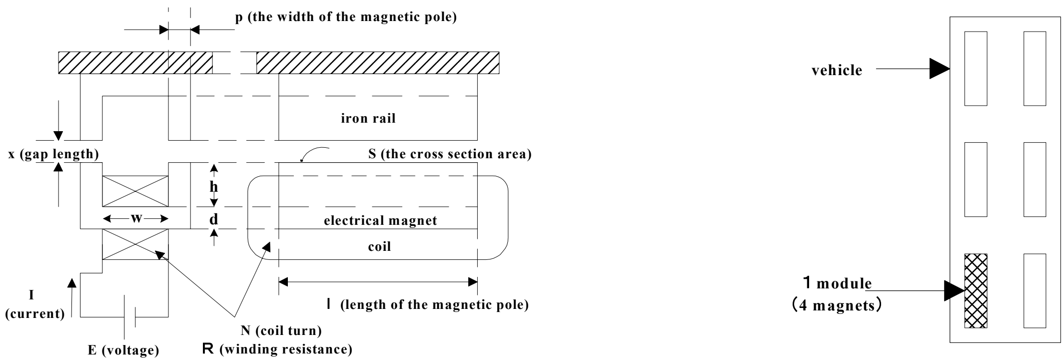
From these viewpoints, the design of the synthetic system considering both the static performances (power requirement and power loss in the magnet, weight of the magnet etc.) and dynamic performances (stability, riding comfort, etc, riding comfort etc.) is desired.

Then in this paper, in order to achieve coordination between static and dynamic performances under all conditions for EMS system of medium speed (up to about 200km/h), genetic algorithm, that is suitable for multipurpose optimum control, is proposed and simulations are carried out to coordinate static and dynamic performances.

2 Numerical model

In the following discussion, the model based on HSST (HSST-03) is used.

Figure 1 shows the vehicle models of HSST. The vehicle is constituted by six modules, each places four staggered magnets. In addition, it is assumed that secondary suspensions (not air suspension but active suspension) are incorporated between module (magnet) part and the passenger cabin.



(a) Analytical model of the levitation system (b) Top view of HSST-03

Figure 1 Vehicle model of HSST

2.1 Derivation of Static Characteristics

For the electromagnetic suspension system in Fig.1 (a), there are two magnet face areas that contribute to the lift force, and this gives rise to the standard force expression

$$F = \frac{B^2}{2\mu_0}(2pl) \tag{1}$$

The direction of this force is upwards towards the guideway.

To derive an expression for the airgap flux density, resistance of the magnetic circuit ($=R_m$) is needed. From Fig.1,

$$R_m = \frac{2p + w + 2h}{\mu_c pl} + \frac{2z}{\mu_0 pl} + \frac{2p + w}{\mu_g t_g l} \tag{2}$$

where t_g is the guideway thickness. If the flux density is assumed to remain constant in the magnet's core as well as in the guideway, then $\mu_c=\mu_g=\mu_i$, and this gives

$$R_m = \frac{1}{\mu_0 pl}\left[2z + \frac{\mu_0}{\mu_i}\{2h + (1+\alpha)b\}\right] \tag{3}$$

where $\alpha=p/t_g$ and b=total width of magnet=$2p+w$. Thus for an arbitrary ampere-turns $AT(=kwhJ)$, the airgap flux density is given by using eqn.(3)

$$B = \frac{\mu_0 kwhJ}{\left[2z + \frac{\mu_0}{\mu_i}\{2h + (1+\alpha)b\}\right]} \tag{4}$$

For operational reasons, it is desirable to keep the airgap flux well below the saturation limit. The basic index of magnet performances is its force capability and input power requirements. The two parameters which are widely used to quantify these are lift force to magnet (core and coil) weight (*Rlw*) and lift force to input power (*Rlp*).

Combining eqns. (1) and (4), the attraction force between the magnet and ferromagnetic reaction surface, up to saturation, is given by

$$F = \frac{\mu_0 pl(kwhJ)^2}{\left[2z + \frac{\mu_0}{\mu_i}\{2h + (1+\alpha)b\}\right]^2} \tag{5}$$

If γ_i and γ_w are the densities of the magnet iron core and winding, then from Fig.1

$$\begin{aligned} &\textit{weight of the magnet core,} \quad W_i = \gamma_i\{2(h+d)p + wd\}l \\ &\textit{weight of the excitating winding} \quad W_w = \gamma_w k\{2l + \pi(d+h)\}wh \end{aligned} \tag{6}$$

Combining eqns. (5) and (6), the lift force to magnet weight ratio is given by

$$R_{lw} = \frac{F}{W_i + W_w} = \frac{\mu_0 pl(khwJ)^2}{\left[\gamma_i\{2(h+d)p + wd\}l + \gamma_w k\{2l + \pi(d+h)\}wh\right]\left[2z + \frac{\mu_0}{\mu_i}\{2h + (1+\alpha)b\}\right]^2} \tag{7}$$

If ρ is the specific resistance of the wire, then the resistance of the winding is given by

$$r = q\frac{2l+\pi(d+h)}{kwh} \tag{8}$$

Thus for any current *i* (=*kwhJ*), the copper loss in the excitation winding is

$$P_0 = i^2 r = q\left[\frac{2l+\pi(d+h)}{kwh}\right](kwhJ)^2 \tag{9}$$

$$= qkwh\{2l+\pi(d+h)\}J^2$$

Combining eqns. (5) and (9), the lift to power ratio is given by

$$R_{lp} = \frac{F}{P_0} = \frac{\mu_0 kplwh}{q[2l+\pi(d+h)]\left[2z+\frac{\mu_0}{\mu_i}\{2h+(1+\alpha)b\}\right]^2} \tag{10}$$

2.2 Design of Control Model

Figure 2 shows the model, which is used for analyses. The model consists of a body and two modules. The module that places former part of the body is called as “former module”, and the other module is called as “rear module”. The mass of the body is *M/3* where *M* is the total mass of the vehicle.

Figure 3 shows a block diagram based on above model. The compensator for levitation is designed by state feedback. Table 1 summarizes the parameters used in the analysis.

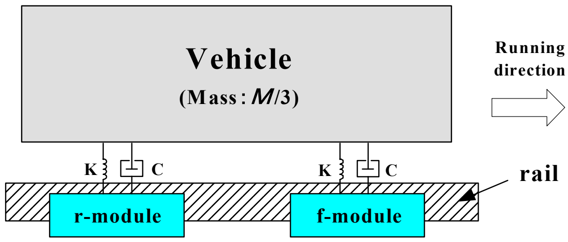


Figure 2 Vehicle model

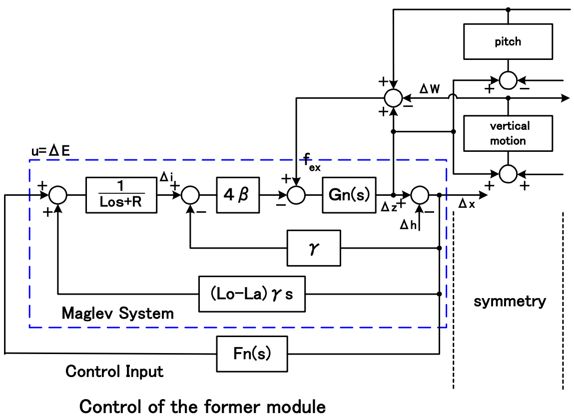


Figure 3 Block diagram of levitation model

Table 1 Dimensions of magnetic levitation system

Electromagnet	
Steady-state gap length	*xo*
Excitation current	*io*
Coil resitance	*R*
Coil inductance	*Lo*
Operating current – operating gap length ratio	*γ*
Change of the attractive force for exciting current	*β*
Mogule	
Mass	*m*
Vehicle	
Mass	*Mg*
Pitcting equivalent mass	*Mφ*
Secondary suspension	
Spring constant	*K*
Damping constant	*C*

In Fig.3, transfer function between the guideway deviation (Δh) and the primary suspension clearance (Δx) is;

$$g_x(s) = \frac{\Delta x(s)}{\Delta h(s)} = \frac{b(s)+c(s)-a(s)}{a(s)-c(s)} \tag{11}$$

Where

$$a(s) = 1 - \frac{4\beta\gamma}{ms^2} + \frac{4\beta}{(L_0 s+R)\cdot ms^2}\{k_a s^2 + k_x + k_v s + (L_0 - L_a)\gamma s\} + \frac{Cs+K}{ms^2}\left\{1 + \frac{Cs+K}{M_\phi s^2 + 2Cs + 2K} - \frac{Cs+K}{M_g s^2 + 2Cs + 2K}\right\}$$

$$b(s) = \frac{4\beta}{(L_0 s+R)\cdot ms^2}\{k_x + (L_0 - L_a)\gamma s\} - \frac{4\beta\gamma}{ms^2} \qquad c(s) = \frac{(Cs+K)^2}{ms^2}\left\{\frac{1}{M_g s^2 + 2Cs + 2K} + \frac{1}{M_\phi s^2 + 2Cs + 2K}\right\}$$

(12)

Further, the function corresponding to the absolute position of the cabin (ΔW) is;

$$g_a(s) = \frac{\Delta W(s)}{\Delta h(s)} = \frac{(Cs+K)\cdot b(s)}{\{a(s)-c(s)\}\cdot(M_g s^2 + 2Cs + 2K)} \tag{13}$$

Using above equations in the context of design of the primary suspension system, the power spectral density (PSD) of the gideway-primary suspension clearance is

$$S_{xw}(w) = g_x(jw)\cdot g_x(-jw)\cdot S_t(w) \tag{14}$$

Where $S_t(\omega)$ is the PSD of guideway deviation. A and v are respectively constant (guideway roughness) and vehicle longitudinal velocity.

Similarly, the PSD of the cabin acceleration (secondary suspension) is;

$$S_{aw}(w) = (jw)^2 g_a(jw)\cdot(-jw)^2 g_a(-jw)\cdot S_t(w) \tag{15}$$

3 Application of genetic Algorithm

3.1 Genetic Algorithm

The Genetic Algorithm is what optimizes the system by modeling Darwinian evolutionary processes. The fundamental flow of the genetic algorithm is shown in Fig.4.

In GA, the population that consists of multiple individuals is set in the computer. The selection and reproduction are executed so that a new generation (i.e., the next generation) is generated using operators patterned after the Darwinian principle of reproduction and survival of the fittest and after naturally occurring genetic operations. By applying GA operators etc., for instance, crossover, mutation, the new solution is created and is searched. If such a process is repeated several times, the appearance of the excellent individual can be expected. Then, optimum solution or the solution, which corresponds to it, is finally obtained.

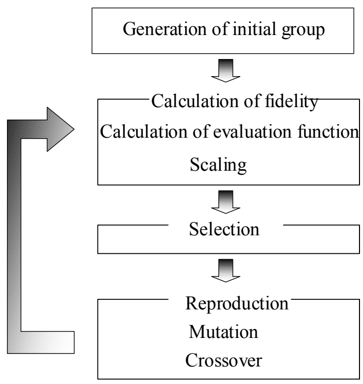


Figure 4 Procedure of the optimum value search by GA

3.2 Evaluation method

Equation (16) and (17) are used as an evaluation function in order to achieve the above-mentioned requirements. In this paper, first of all, the optimum design of the magnet is done by (16) based on (7) and (10). Vehicle dynamics is evaluated by using (17) on that. F_{samp},P_{samp},W_{samp}, S_{xwr} and S_{awr} are references obtained by using values used for an actual HSST-03 vehicle.

$$k_f\left(\frac{|F-F_{samp}|}{F_{samp}}\right) + k_{lp}\left(\frac{P_{samp}}{P}\right)^2 + k_{lw}\left(\frac{W_{samp}}{W}\right)^2 \quad \cdot\cdot\cdot (16)$$

$$k_x\sum\left(1-\frac{S_{xwr}}{S_{xw}}\right)^2 + k_a\sum\left(\frac{S_{aw}}{S_{awr}}\right)^2 \quad \cdot\cdot\cdot (17)$$

3.3 Representation of parameter

In this paper, the goal is to search optimum parameters of levitation system within arbitrary fixed range in order to realize more high-speed and economically systems.

Structure and representation example of the chromosome concerned with dynamic characteristics is shown in Fig.5. The chromosome used in this paper with respect to vehicle dynamics is composed of two elements of control system and secondary suspension. The length of the chromosome is 40 bits and 8 bits are respectively allocated in all elements.

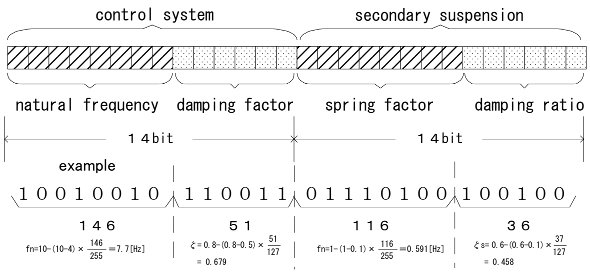


Figure 5 Example of the chromosome

As a fitness measure, chromosome strings are converted into the decimal number. Then, fitness value is evaluated by simulation results using the obtained parameters.

3.4 Selection of parameter

GA parameters shown in Table 2 have been determined by several trials and error to satisfy following conditions.

1. The population of individual is 50 in order to maintain diversity.
2. For wide search, individuals are selected so that there are no identical ones in a generation.
3. By several trials and error, the mutation probability is set low, and the crossover probability is set high.
4. For the searching ability improvement, elite strategy and scaling technique are adopted.

Table 2 GA parameters

gene number	elite number	scaling window	mutation probability	crossover probability
50	8	2	0.2	0.9

3.5 Simulation method

The flow of the whole simulation is shown in Fig.6.

GA lacks reproducibility and certainty because GA is a probabilistic algorithm. The statistical processing is required in order to get the conclusion from simulations. Further, in the genetic algorithm, because it simulates the evolutionary processes, much calculation time is required in order to carry out evaluation, selection, and genetic operation of all individuals. Therefore, the search here has been carried out in off-line to design the optimum suspension.

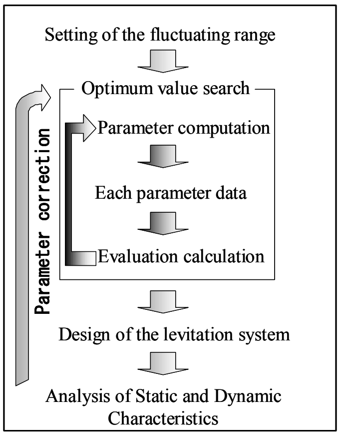
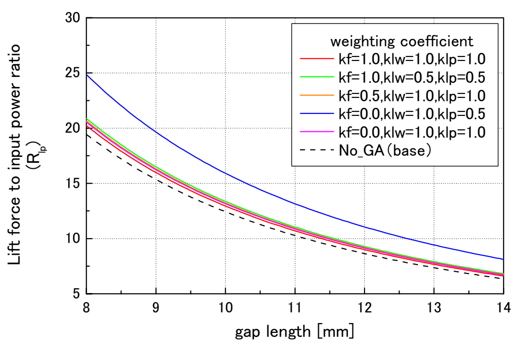


Figure 6 Flow of the whole simulation

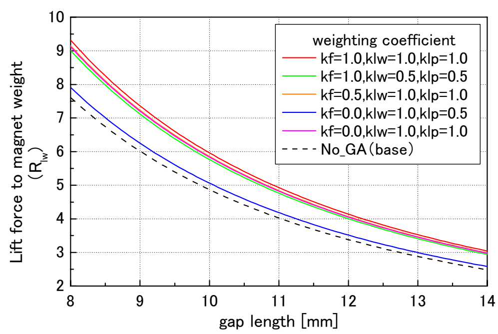
4 Simulation results and discussion

4.1 Steady state characteristics

Figure 7 shows the simulation results in the steady state based on (16). When GA is applied, the evaluation index is improved compared with the case when GA is not applied. There is a trade off between those two indexes in the case when GA is applied. Therefore, appropriate weighting coefficients have to be set according to the demand.



(a) Variation of lift to power ratio



(b) Variation of lift to weight ratio

Figure 7 Static characteristics of the magnet

4.2 Dynamic characteristics

4.2.1 Step Response

Figure 8 shows step responses when the vehicle passes through the difference in the rail level with 1mm.

The overshoot is not remarkable except for the case of *kx/ka*=10. Though there is a little difference at the response speed by the weighting coefficient, responses of gap length uniformly settle in both cases and vehicle does the constant gap running.

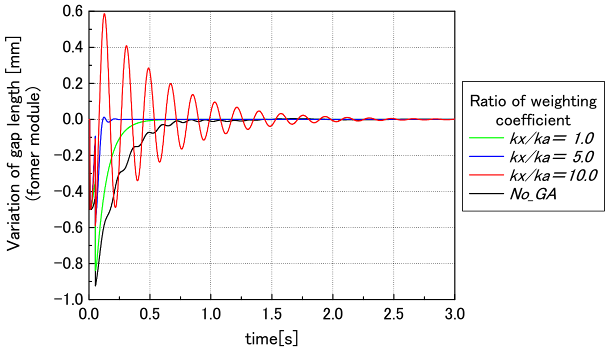


Figure 8 Step responses for the rail level difference (Δh=1[mm])

4.2.2 Rail modeling and responses

Figure 9 shows the deflection of the rail using in simulations. Deflection of the rail is assumed as a sinusoidal wave. The span length of the rail is 20[m], and the deflection at the center between girders is 2[mm], that is, rail is a sinusoidal wave with amplitude 1[mm] and a period 20[m]. Gap length responses are shown in Fig.10 when the vehicle is running in medium-speed (200km/h). The gap sensor is assumed to be arranged before and behind the module, and the detected values are leveled before they are input to the controller.

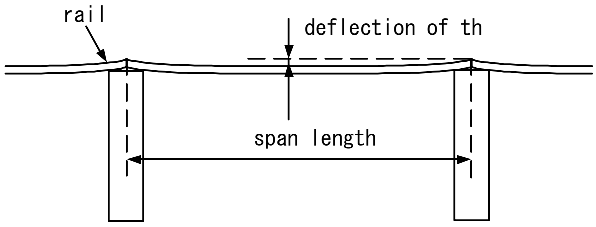


Figure 9 Deflection of the rail

First, in the case when GA is not applied, vibration of module has large amplitude, and this vibration affects the riding comfort.

Next, the case in which GA is applied, the vibration range for the guideway variation is different according to weight.

In the case *kx/ka*=5, the responses of gap length are held small and the sufficient controllability is retained. On the other hand, in the case *kx/ka*=1, the vibration of module is as large as that of the case without GA. Therefore, the variation range tends to increase, when weighting coefficient *kx* is set small.

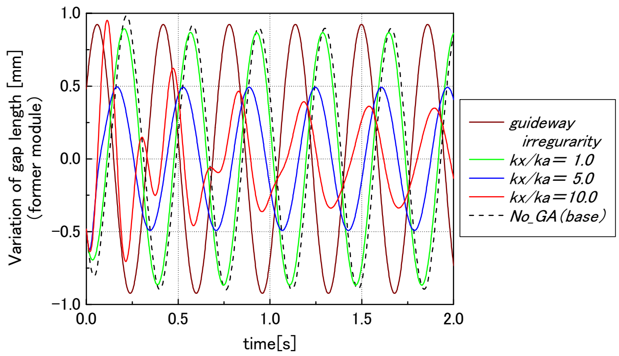


Figure 10 Gap length responses for the deflection of the track

4.2.3 Analysis of riding comfort

Figure 11 shows the analytical results of riding comfort. All simulated cases have been satisfied UTACV riding comfort standard, which the ISO determines. It is shown that all cases achieve enough riding comfort below the criterion level when the weighting factor is appropriately set. The frequency characteristics tend to decrease when weighting coefficient *kx* is set small.

By the way, human body is the most sensitive to the vibration of 4 to 8[Hz] frequency on the vertical direction.

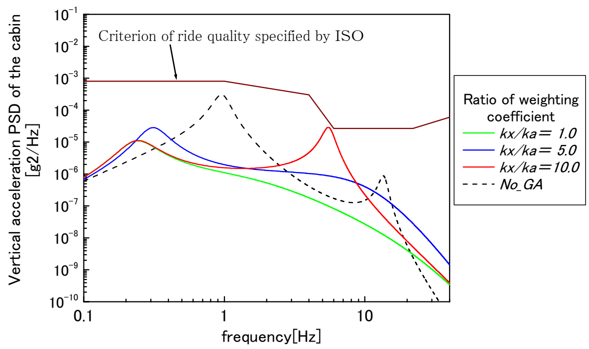


Figure 11 Frequency characteristics of vertical acceleration of the vehicle body

There are two peaks around several Hz in the case without GA, on the other hand, there is no peaks and the PSD is decreased around most human-sensitive frequency, when GA is applies. From these results, GA is able to improve riding comfort.

4.2.4 Effect of weighting coefficient

The required characteristics is not always satisfied by use of GA. Adequate weighting coefficient should be set in order to apply GA.

The relation of the trade-off is found between both these functions from search result of the evaluation function by use of GA. It is shown that the optimum-weighting coefficient exists for searching and GA is useful for applying to the control problem.

5 Conclusion

In order to achieve design optimization of the electromagnetic suspension system (EMS) for magnetically levitated vehicle on its dynamic performance and weight, a design scheme based on the genetic algorithm is proposed.

From simulation results, GA gives the control parameters flexibly against various requirements. The control characteristics of the system are improved in comparison with the conventional optimum control theory. It is concluded that various evaluations are possible by applying GA and realization of Maglev system with good characteristics can be expected. In addition, we confirmed the usefulness of GA for control problem.

Further study will be carried out to achieve coordination between static and dynamic performances and then the design optimization of the synthetic system.

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