# Invitation to Levitation Control: Problems Expecting a Smart Solution

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## ABSTRACTS :

Electromagnetic suspension (E.M.S) type levitation system is studied in the control system design viewpoint. Dynamic characteristcs in theoretical analysis as well as hardware implementation is considered.

Open loop unstable, non-linear and timevarying charateristics are reviewed in the theoretical section, while levitation control system for multi-vehicle train as well as magnet drive system is reviewed in the practical section. This paper suggests not only some well-known problem appearing in levitation control system design but also a subtle problem and solution candidates. But there exist many unmentioned problems waiting for a smart problem solver.

## 1. Introduction

Magnetic levitation system is classified by E.D.S (electrodynamic suspension) and E.M.S (electromagnetic suspension) in the large.

The former uses repulsive force of magnets appearing something like super conducting magnets, while the latter uses attractive force of magnets appearing between iron and magnets. In this paper E.M.S system is dealt in the control system design and implementation viewpoint from a single magnet model to a maglev train model.

In the theoretical control points, the following charateistics and its solution candidates are surveyed :

- open-loop unstable system
- relative degree and non-minumum phase system
- non-linear system and non-linear control
- time varying system and adaptive robusf control
- required degree of freedom and multivariable design.

In the practical system implementation view points, the followings are surveyed :

- accessible information
- disturbance signal from guideway joint gap
- secondary suspension
- total control system for maglev train.

## 2. Control ststem design strategy related with system structure

### 2.1 Levitation force

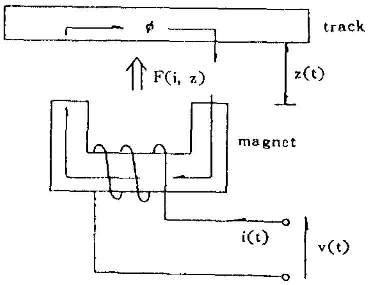

Fig. 1 Magnetic Levitation System

Single magnet levitation system is shown in Fig.1. If the current flowing in the magnet coil is bigger than the equilibrium current, the attractive force becomes bigger than the magnet weight and magnet will be attached to the guideway. If the current is smaller than the equilibrium current, the attractive force is smaller than magnet weights and the magnet will be dropped to ground level. This is the physical concept of unstable equilibrium point.

Neglecting the saturation effefts, force, voltage, current relation can be summarized as follows.

$$F(i,z) = K_1 \left[ \frac{i(t)}{Z(t)} \right]^2 \text{-------------} (2.1)$$

$$V(t) = Ri(t) + \frac{2k_1}{Z(t)}\frac{di(t)}{dt} - \frac{2K_1}{Z^2}i(t) \cdot \frac{dz(t)}{dt}$$

------------------(2.2)

$$m\ddot{z}(t) = -F(i,z) + f_d(t) + mg \quad \text{----------}(2.3)$$

Assuming equilibrium point (io,zo),

$mg = -k_1 \left[ \frac{i_o}{Z_o} \right]^2$ can be achieved.

Linearization by taylor series method makes the open loop poles

$$S_1 = -\frac{R}{L_o}$$

$$S_2 = -\frac{L_0 K_z}{2mR} \pm \sqrt{\left[\frac{L_0 K_z}{2mR}\right]^2 + \frac{K_z}{m}} ,$$

------------(2.4)

where $K_z = \mu_0 N^2 \dfrac{A i_0^2}{2 Z_0^3}$

The linearized open loop system has a right half plane pole and this makes the system unotable.

## 2.2 Guidance control strategy

Two kinds of concept can be used. One is to design sperate guide magnets to generate a lateral force, which is shown in Fig.2 and lateral mode is open-loop unstable.

The other is to use an open-loop stable characteristics of lateral mode of levitation magnet. When a magnet is levitated, lateral force direction is toward the guideway and this lateral force makes the levitated vehicle return to the central position against disturbance force in the limit of magnet's force. But in this case, generated lateral force against lateral disturbance is almost propotional to the displaced gap and the suspended mass moves like a mass on a spring. This concept is implemented by linearly arraryed levitation magnets.

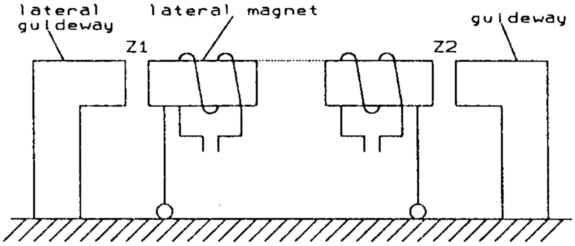

Fig. 2 seperate guidence method

To introduce an active lateral force compensation concept, magnet array is changed. Instead of linear array, staggered magnet array without any seperate lateral magnet can be used to make an active lateral force compensation.

Fig.3 shows conceptual differences between linearized array method and staggered array method.

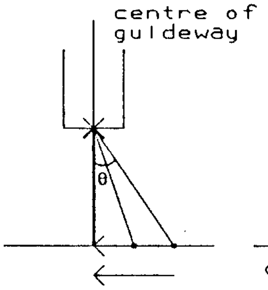

Fig3.a linear array

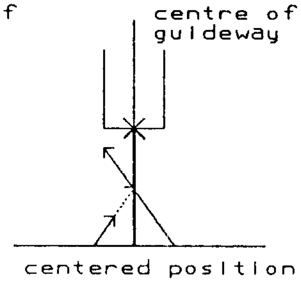

Fig 3.b stagger array

$f_g$ in Fig.3.a is function of magnet centre position.

$f_g = f_l \tan\theta$ ------------------------(2.5)

$f_g = M g$ = constant

For constant operating gap, $\tan\theta$ is proportional to latetal displacement, y. So eq.2.5 can be changed to $f_g = k' y$ and guidence force es proportional to displacement.

This is a force equation of spring motion and zero guidance force at centered position.

In Fig.3.b, related force equation can be summarized as

$f_g = f_1 \cos\theta_1 - f_2 \cos\theta_2$

$f_l = f_1 \sin \theta_1 + f_2 \sin\theta_2 = M \cdot g,$

Where f1, f2 can be controlled on a curve varying from 0 to $f_l \cdot \sec\theta$ for a given θ,

Fig.4 shows a possible guidance force zone for a typical system of operating levitation gap 10mm and each magnets staggered 5 mm to each side.

θ=45° means control position of magnets are displaced by 10 mm from the central position of guideway.

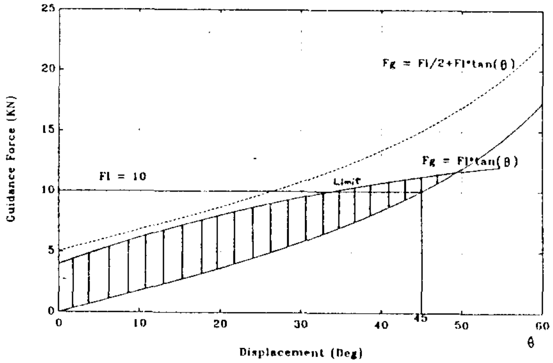

Fig.4. guidance force curve

Botton line indicates guidance force of linearly arrayed magnets. But in the parctical design stage, magnet heating and saturation limits maximum controlled current below the limit. But for small θ, levitation force can be increased quite more than the linearized array method without touching the limit curve.

In the seperate guidance magnet method, two guidance magnets are controlled to maintain constant lateral position. If the operating gap is too small, time constant of the magnets makes control difficult, while size and mass of the magnets make problem if the operating gap is big. And in Fig.2, lateral system is open-loop unstable and it needs a stabilizing controller, while the staggered method uses an open-loop stable charateristics. By desiging closed loop poles representing guidance mode, guidance stiffness and magnet heating and saturation can be solved simultaneously.

## 2.3 structure and control degrees of freedom

Dynamics of vehicle is dependent on the structure of vehicle. Two kinds of bogie pattern is considered here. One is tie-bar structure shown in fig.5a. Left magnet array, usually 4 magnets, and right array are combined by a almost rigid body. In this model, each module is linked very tightly and each module has a very little degree of freedom.

This module can be considered as a rigid plate. As propulsion is another problem controlled by LIM, 5 modes including sway, pitch, roll, heave and yaw need to be controlled.

In the anti-roll beam pattern, each module has quite big freedom compared with tie-bar pattern. So left and right module do not need any information from other right and left module. In this case for the control of vehicle, we have only four independent source for each module and 4 is the maximum degree of freedom required and we can implement.

The position of secondary suspension is another factor for decision of control strategy. Secondary suspension located at the two end-position of module has the effect of increasing the momentum inertia of module, while one suspension located at the middle of a module reduces the actual inertia. For big inertia system, the needs of pitch control is increased.

This is shown in Ref.[1].

## 2.4 Considerations on robust controller design

As shown in eq.(2.1) and (2.2), levitation system is inherently non-linear. In levitation model, operation gap is not changed very often. But needs for changing operating gap exist. In the linear control method, change of operating gap demands re-tuning of control gain. But if non-linear compensation is ahieved, changing of operating gap doesn't make any troubles. For this purpose non-linear feedback linearization can be used[2,3].

The linearized model is zero free system with three poles. Open-loop pole is function of resistance R. As resistance is changed by the temperature, open-loop pole is a time varying parameter. So a kind of adaptive controller can be used to solve this time varying problem. Operating temperature range is about from -30°C to 100°C. For well chsen operating temperature, maximum 20% of resistance can be changed. But another problem to be considered is this system's relative degree is three. Relative degree bigger than 2 always makes the digitized system nonminimum phase for small sampling time and adaptive control algorithm should be chosen carefully. Sigle step prediction controllers like minimum variance algorithm can not be applied here. Self-tuning pole-placement control simulaion was performed in [4].

Some phenomena which can not be measured in a levitated module is guideway vibration. This is another very important problem to be solved. Ideas to design an observer from gap, acceleration/velocity, magnet current signals are suggested [5].

# 3. Levitation control system for MAGLEV-train

## 3.1. Digital Control System

In inplementation stage, choice of control device is the first element to be decided. Digital system has many merits compared with analogue system.

- Reliability

System reliability depends on the number of components and reliability of each component. In analogue system, for a simple multiplication or addition of a signal, several number of devices are reguired. But in digital system, lots of calculations can be carried out by a digital device. Digital implementation can reduce quite a lot the number of used devices compared with analogue implementation.

The bigger the system is, the bigger the digital implementation effect is. Most of the digital devices achieved sufficient reliability, digital implemetation has a big merit in reliable system implementation.

In the view points of fault-tolerant system, digital technology can be used to implement so called "voting system". 2out of 3 method is the most well known technology and can be implemented in MAGLEV control system.

- Uniformity

In mass-production stage, uniformity of the product is an essential evaluation point. In anaolgue system tuning, to get a uniformity in the system characteristcs, lots of time and efforts are necessary compared with digital system. In digital system, lots of checking procedure for uniformity can be performed by a routine work and excellent unifornity can be achieved.

- S/W flexibility

Many kinds of software program can be changed without any hardware change in digital method. But in analogue method even a change of freguency band or addition of simple feedback loop needs some hardware change. In analogue technology, simple linear calculation and limit circuit can be implemented, while most of the nonlinear calculations, predictions and identification algorithm can not be operated. As mentioned in section 2, nonlinear or adaptive method is needed for a smart solution and digital method is prefered.

- Information handling

For a large scale system, information transfer and handling is very important as well as control loop for local control action. Digital system can be used very nicely for information handling such as monitoring, diagnosis and supervisory control.

## 3.2. Design concept of levitation control for MAGLEV train

The author suggests the network system shown in Fig 6. In maglev train, every module needs to be controlled independantly. But the controlled situation should be known to operator or control system to keep a small fault from being enlarged to an accident or disaster.

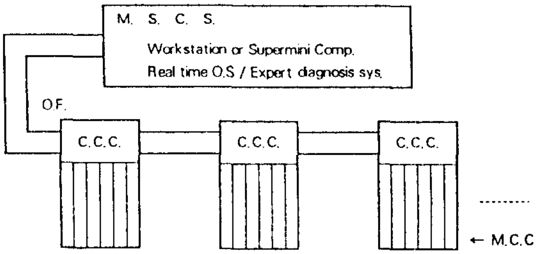

Fig. 4 Control system for maglev train

- M.S.C.S : Monitoring & supervisory control system
- V.C.B : Vehicle control box
- M.C.C : Module control card
- C.C.C : Communication control card
- O.F : Duplicated optical fiber for communication

V.C.C Contains as many as the number of modules in a vehicle and a C.C.C.
M.S.C.S monitors and perform supervisory control the vehicle though V.C.B.s by O.F.. To change easily the number of vehicler in a train, serial communication with multi-drop is suggested. To increase the system reliability, two way optical-fiber link is prefered. Each module control card control each module of 4 magenets by up-to-dated control theory and a powerful candidate for M.C.C. hardware may be a D.S.P based processors with matching accesaries.

# 4. Conclusion

Characteristics of E.M.S type levitation system is surveyed. In the system modelling viewpoint, non-linear, time-varying, open-loop unstable and non-minimum phase characters are reviewed. Design of guidance control and degree of control freedom related with vehicle structure is shortly mentioned.

In the practical inplemention stage, a pototype design of maglev - train control system is suggested based on a top-level concurrent technology.

## 5. References

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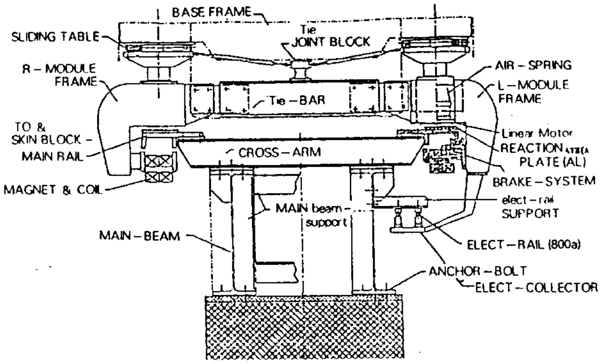

Fig 5.a tie-bar type structure

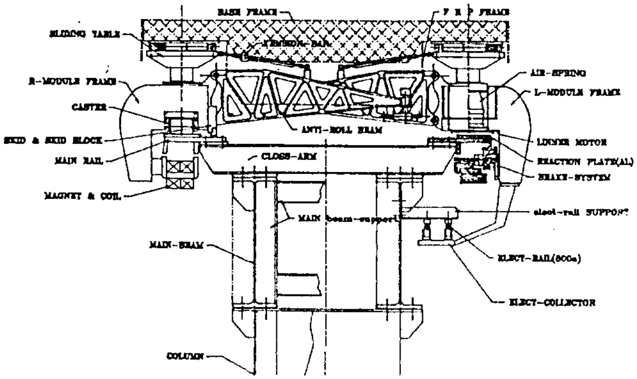

Fig 5.b anti-roll beam type structure