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A study for Levitation and Guidance Control System Design

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Abstract : Control system design for attraction type Maglev system is dealt in this paper. Characteristics of levitation and guidance control is explained and a kind of active guidance controller performance is compared with passive guidance control.

Also, a method of using absolute and relative information simultaneously is adopted for levitation control. All the methods studied performed very well in the experiments as well as simulation.

1. Problem Statements

Control of magnetic force is known to be a new technology in developing clean room automatic system and new transportation system called Maglev. This paper is concerned in developing an attraction type Maglev system. System to be controlled (i.e.levitated and guided) consists of guideway and at least 2 staggered magnets. For the control of the system, D.C. power supply, chopper for power control, transducers such as air gap sensor, accelerometer and C.T. are necessary. With the given system constranits, controller determines the control quality such as acceleration limit, steady state error, stiffness to the disturbance and flexible guideway vibrations.

Fig 1.1 Shows the structural model of levitation & guidance system. Characteristics of the model can be summarized as

1) open - loop unstable in vertical direction
2) lateral stability is guaranteed if vertical system is stable
3) magnet force relation is non - linear
4) multi - input multi - output system

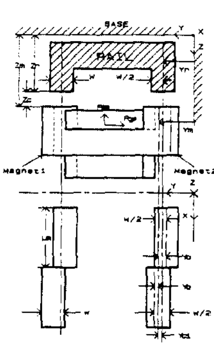


Fig 1.1 Front and side view picture of staggered magnet & guideway

Fig 1.2, 1.3 show vector force relation in vertical lateral directions. First concept in levitation / guidance control is to control only the vertical direction. In this case the lateral force comes as the result of vertical control. As two magnet voltage are same, two magnet currents are almost same. The sum of vertical force components of 2 magnet should be the same as the gravitational force-mg. But, the lateral force generated by the magnets is vector sum of the lateral components of 2 forces. So the lateral force is dependent on the terms of the levitated position.

If the magnet is located in the central point, lateral force sum is zero. The bigger lateral dispacement is the bigger lateral force becomes, which is nearly proportional to the displacement. This characteristics makes lateral motion of the system like a motion of sprung mass motion. This problem can be solved by suppling different voltage to the magnets.

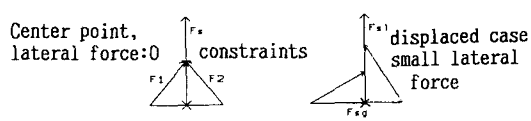


Fig 1.2 Same voltage control vector diagram

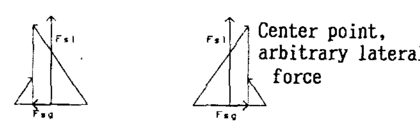


Fig 1.3 2 voltage control vector diagram

If combination of voltage which makes the vertical force sum constant and lateral force vector sum arbitrary is possible, to control the system stiffly to lateral disturbance is possible. This is the starting point of levitation & guidance control of magnetically suspended system, and improves the ride guality, while the vehicle is following a round guideway. This physical concept is controllability in the mathematical form of 2 input 2 output (multi-variable) system. Another important point to control the magnetically suspended mass is flexibility of guideway. To solve this problem, comparative study of using absolute and/or relative velocity is carried out.

The following section 2 explains force relations between guideway and magnets. Guidance control system design concept follows in section 3. A concept of observer for flexible system is applied to reduce vibration problem in section 4.

Some observations and heuristic comments are made in conclusion section 5.

2. System Modelling [2,3]

Suspension & Guidance forces generated by one side magnet in a pair of staggered magnets are given to equations (2.1), (2.2) and voltage and current relations are given to equations (2.3),(2.4) too.

$$F_s=\alpha_s\left[\frac{i}{Z_c}\right]^2\cdot\left(1+\frac{2Z_c}{\pi W}-\frac{2Y_c}{\pi W}\tan^{-1}\frac{Y_c}{Z_c}\right)=\alpha(Z_c,Y_c) \quad (2.1)$$

$$F_g=\alpha_g\left[\frac{i^2}{Z_c}\right]\tan^{-1}\frac{Y_c}{Z_c},\ \alpha_g=\frac{\mu_o l_m\cdot n^2}{2\pi}\ \text{if}\ Y_c=0,\ f_g=0 \quad (2.2)$$

Where,

$$\alpha_s=\frac{\mu_o\cdot l_m\cdot W\cdot n^2}{4},\quad \alpha[Z_c,Y_c]=\left[1+\frac{2Z_c}{\pi W}-\frac{2Z_c}{\pi W}\tan^{-1}\frac{Y_c}{Z_c}\right]$$

and

$$L=L_\alpha+L_\beta\frac{1}{\sqrt{Z^2{}_c+Y^2{}_c}},\qquad L_\beta=\frac{\mu_o\cdot l_m\cdot W\cdot n^2}{2} \quad (2.3)$$

$$e = Ri+\frac{dLi}{dt} \quad (2.4)$$

Where, l_m : length of magnet , $L\alpha$: leakage inductance
i : current, n : coil turns
R : coil resistance, μ_o: permeability in vacuum

From these equations, we can find that force, current, and airgap relation is non - linier.

If these equations is applied to a pair of staggered magnets, dynamic equation of vertical & lateral directions and circuit equation of each magnet is given to (2.5) ~ (2.8)

$$M\frac{d^2Z_{m1}}{dt^2}=9.8M-\alpha_s\left[\frac{i_a}{Z_c}\right]^2\cdot\alpha(Z_c,Y_o+Y_{c1})-\alpha_s\left[\frac{i_b}{Z_c}\right]^2\cdot\alpha(Z_c,-Y_o+Y_{c1})+f_{sd} \quad (2.5)$$

$$M\frac{d^2Y_{m1}}{dt^2}=-\alpha_g\frac{i_a{}^2}{Z_c}\tan^{-1}\frac{Y_o+Y_{c1}}{Z_c}-\alpha_g\frac{i_b{}^2}{Z_c}\tan^{-1}\frac{-Y_o+Y_d}{Z_c}+f_{gd} \quad (2.6)$$

$$e_1=\left[R_a-\frac{Z_c\cdot L_\beta}{(Z^2{}_c+(Y_{c1}+Y_o)^2)^{3/2}}\cdot\frac{dZ_{c1}}{dt}-\frac{(Y_{c1}+Y_o)\cdot L_\beta}{(Z^2{}_c+(Y_{c1}+Y_o)^2)^{3/2}}\cdot\frac{dY_{c1}}{dt}\right]\cdot i_1+\left[L_{\alpha 1}+\frac{L_\beta}{(Z^2{}_c+(Y_{c1}+Y_o)^2)^{1/2}}\right]\cdot\frac{di_1}{dt}-i_o\cdot\frac{Z_c\cdot L_\beta}{(Z_c^2+(Y_{c1}+Y_o)^2)^{3/2}}\cdot\frac{dZ_{c1}}{dt}-i_o\frac{(Y_{c1}+Y_o)\cdot L_\beta}{(Z_c^2+(Y_{c1}+Y_o)^2)^{3/2}}\cdot\frac{dY_{c1}}{dt} \quad (2.7)$$

$$e_2=\left[R_b-\frac{Z_c\cdot L_\beta}{(Z_c^2+(Y_{c1}-Y_o)^2)^{3/2}}\cdot\frac{dZ_{c1}}{dt}-\frac{(Y_{c1}-Y_o)\cdot L_\beta}{(Z_c^2+(Y_{o1}-Y_o)^2)^{3/2}}\cdot\frac{dY_{c1}}{dt}\right]\cdot i_2+\left[L_{\alpha 2}+\frac{(Y_{c1}+Y_o)\cdot L_\beta}{(Z^2{}_c+(Y_{c1}-Y_o)^2)^{3/2}}\right]\cdot\frac{di_1}{dt}-i_o\frac{Z_c\cdot L_\beta}{(Z_c^2+(Y_{c1}-Y_o)^2)^{3/2}}\cdot\frac{dZ_{c1}}{dt}-i_o\frac{(Y_{c1}-Y_o)\cdot L_\beta}{(Z_c^2+(Y_{c1}-Y_o)^2)^{3/2}}\cdot\frac{dy_{c1}}{dt} \quad (2.8)$$

The first step in designing control system is linearization by Taylor series method.

Linearizing eq. (2.5) ~ (2.8) force relation of vertical & lateral directions is represented as following equations.

$$M\frac{d^2Z_{m1}}{dt^2}=-\beta_s\cdot i_s-2\gamma_s\cdot z_{c1}+f_{sd} \quad (2.9)$$

$$M\frac{d^2Z_{m1}}{dt^2}=-\beta_g\cdot i_g+2\xi_g\cdot z_{c1}+f_{gd} \quad (2.10)$$

Where

$$\beta_s=a_s\left[\frac{i_o}{Z_o}\right]\cdot\frac{2\lambda_{1s}}{i_o},\quad \gamma_s=\frac{i_o\lambda_{1s}-Z_o\lambda_{2s}}{2\lambda_{1s}Z_o}$$

$$\beta_g=\frac{2\cdot a_g\cdot i_o}{Z_o}\tan^{-1}\frac{Y_o}{Z_o},\quad \xi_g=\frac{i_oZ_o}{2\cdot(Y^2{}_o+Z^2{}_o)\cdot\tan^{-1}(Y_o/Z_o)}$$

$$\lambda_{1s}=1+\frac{2Y_o}{\pi W}-\frac{2Y_o}{\pi W}\cdot\tan^{-1}\frac{Y_o}{Z_o}$$

$$\lambda_{2s}=\frac{2}{\pi W}\cdot\left[1+\frac{Y^2{}_o}{Z^2{}_o+Y^2{}_o}\right]$$

$$e_{s1}=Ri_{s1}+L_o\cdot\frac{di_{s1}}{dt}-2\xi_s i_o\frac{dz_{c1}}{dt} \quad (2.11)$$

$$e_{g1}=Ri_{g1}+L_o\cdot\frac{di_{g1}}{dt}-2\xi_g i_o\frac{dy_{c1}}{dt} \quad (2.12)$$

Where

$$\xi_g=\frac{Y_oL_\beta}{(Z^2{}_o+Y_o{}^2)^{3/2}},\quad \xi_s=\frac{Z_oL_\beta}{(Z^2{}_o+Y_o{}^2)^{3/2}}$$

$$L_o=L_\alpha+L_\beta\frac{1}{(Y^2{}_o+Z_o{}^2)}$$

Now state space model is represented to eq. (2.13) using the linearized eq. (2.9) ~ (2.12).

$$\begin{bmatrix}\dot{Z}_{c1}\\ \ddot{Z}_{c1}\\ \dot{i}_1\\ \dot{Y}_{c1}\\ \ddot{Y}_{c1}\\ \dot{i}_2\end{bmatrix}=\begin{bmatrix}0&1&0&0&0&0\\ \frac{2\cdot\beta_s\cdot\gamma_s}{M}&0&-\frac{\beta_s}{M}&0&0&\frac{\beta_s}{M}\\ 0&\frac{i_o\cdot\zeta_s}{M}&-\frac{R_a}{L_{o2}}&0&\frac{i_o\cdot\zeta_g}{M}&0\\ 0&0&0&1&0&0\\ 0&0&\frac{\beta_g}{M}&-\frac{2\cdot\beta_g\cdot\xi_g}{M}&0&\frac{\beta_g}{M}\\ 0&\frac{i_o\cdot\zeta_s}{M}&0&0&-\frac{i_o\cdot\zeta_g}{L_{o2}}&-\frac{R_b}{L_{o2}}\end{bmatrix}\begin{bmatrix}Z_{c1}\\ \dot{Z}_{c1}\\ i_1\\ Y_{c1}\\ \dot{Y}_{c1}\\ i_o\end{bmatrix}+\begin{bmatrix}0&0\\ 0&0\\ \frac{1}{L_{o1}}&0\\ 0&0\\ 0&0\\ 0&\frac{1}{L_{o1}}\end{bmatrix}\begin{bmatrix}e_1\\ e_2\end{bmatrix} \quad (2.13)$$

3. Controller design

State space model obtained in the preceeding section makes design of basic feedback controller possible.

Here, we start with the limited assumption that guideway is rigid body, while the actual guideway is flexible. In the state space model velocity term is shown and it is generally well known that velocity term is essential in position control. But difference between this problem and position control using a servo-motor is that velocity term has 2 different concepts - absolute velocity of mass and relative velocity between mass and guideway, while derivative of position is mathematically the same as integration of acceleration in other position control problems.

In designing controller, although exact model representing guideway flexibility and irregularity is helpful, difficulties in dynamic modelling of guideway keep us from deriving the exact model.

3.1 Concept of Guidance Control

One pair staggered magnets try to maintain their center on the center of rail without disturbances like winds and curve running.

However, there being disturbances, the response of levitation control system will go bad, and the mechanical non-contact limit of lateral direction will be exceeded.

To solve problems like that, the guidance control is adopted. Block diagram including the guidance control is shown in Fig 3.1. When the design of controller involving guidance control is made, the interaction between suspension and guidance has to be considered.

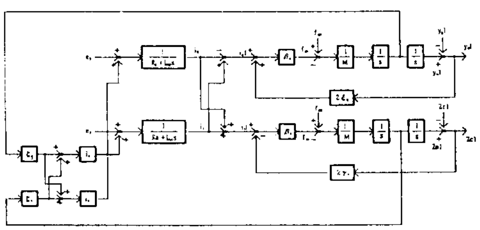


Fig 3.1 Block diagram of staggered magnets (open-loop)

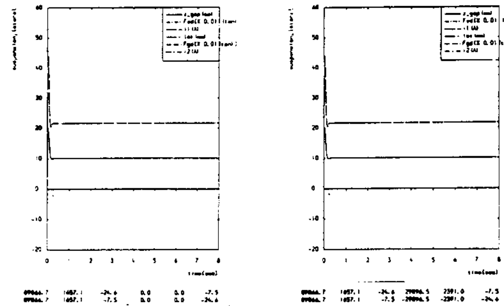
In case of controlling suspension & guidance together , the design of controller can not be made completely independently, but considering the control characteri-tics of vehicle for each of the directions, design under the linear model assumption is possible. For most full-scale magnetically suspended vehicles, the suspension natural frequency is in the 4-10Hz range[4]. Here 6Hz is chosen. Also, damping ratio with which ride guality is concerned is 0.707 for suspension control. 3Hz (natural frequency), and 0.25 (damping ratio) is chosen for guidance control.

And real pole value is chosen -45 for both. With these values, the control gains are obtained for MIMO system and the obtained gains are represented in 2 X 6 Matrix[5].

$$K=\begin{bmatrix} 89866.7 & 1657.1 & -24.6 & 29896.5 & 2391.0 & -7.5 \\ 89866.7 & 1657.1 & -7.5 & -29896.5 & -2391.0 & -24.6 \end{bmatrix}$$

3.2. Simulation

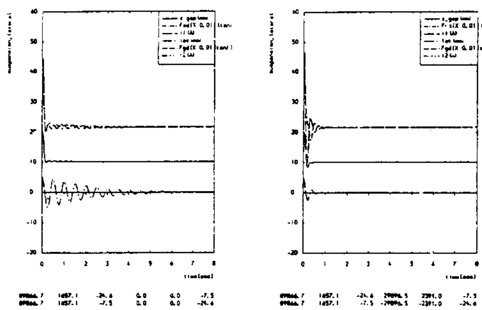
In this section, the results of computer simulation are shown, done using the obtained gain in the preceeding section, and are explained. As long as there are no disturbances and the initial displacement equals 0, the response of control system with guidance control or without guidance control is very similar as shown in Fig 3.2 (a),(b).



(a) (b)

Fig 3.2 (a) System response without guidance control
(b) System response with guidance control
Initial displacement : 0 (mm)
No disturbance

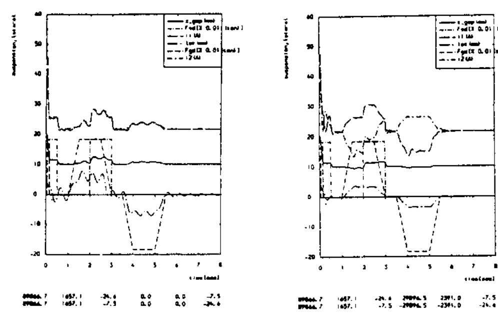
But, if the pair magnets have the +5mm initial displacement from rail center as shown in Fig 3.3 (a),(b), with the guidance control the lateral response is better.



(a) (b)

Fig 3.3 (a) System response without guidance control
(b) System reponse with guidance control
Initial displacement : +5 (mm)
No disturbance

Fig3.4 (a) shows the system response without guidance control in following case -- +5mm initial displacement and the lateral disturbance of 0.1Mg without guidance control. Fig3.4 (b) equals to Fig3.4 (a) in conditions except doing guidance control. Fig 3.4 shows that the system response with guidance control is the better for both of two directions.



(a) (b)

Fig 3.4 (a) System response without guidance control
(b) System reponse with guidance control
Initial displacement : +5 (mm)
Disturbance :
f_{zd} = 0.1 Mg ($0 \le t \le 0.5$ & $2 \le t \le 3$ (sec))
f_{yd} = 0.1 Mg ($0.05 \le t \le 0.15$ & $1 \le t \le 2.5$ (sec))

3.3 Experimental Results[4]

In controlling the suspension of vehicle, if weight balance is maintained between modules (4 Magnet in one side), the lateral displacement does not exist (open loop stable in lateral direction). This fact leads to not using the lateral gap sensor.
The plant for experiment classifies two cases.
First is the one pair staggered magnets, and the other is one vehicle (2 modules).

3.3.1 Experiment for Plant I (one pair staggered Magnet)

- Specification of plant I

Staggered quantit	5 [mm]
Number of turns	200 [turns]
Coil Resistance	11 [Ω]
Coil Inductance	45 [mH]
Pole Width	15 [mm]

To elvaluate the guidance force for this plant, two cases are compared.
case I. Only Suspension Control
case II. Suspension & Guidance Control
The signal of Fig 3.5 (a) is to include the guidance control, but Fig 3.5 (b) is not to do the guidance control.

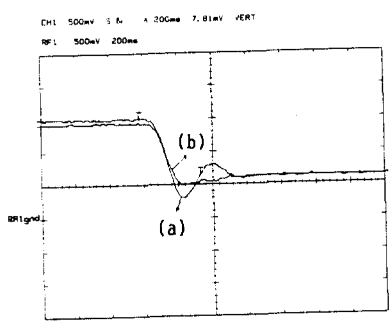
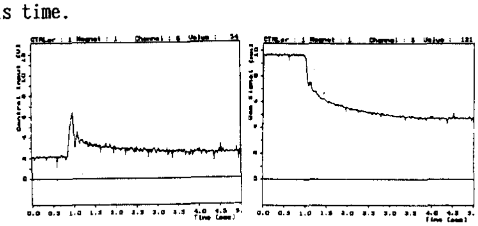
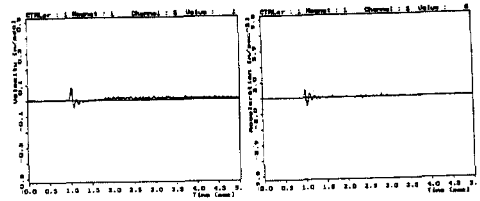


Fig 3.5 Comparison of the only suspension control with suspension & guidance control
(a) Guidance control (b) No guidance control

Briefly mentioning to the experimental methods, as follows. In case of (a), the initial lateral displacement made compulsively is larger than case of (b). This means that the bigger magnitude of lateral disturbances are put. During suspension and guidance control simultaneously, in a moment the lateral disturbances is eliminated. At the very moment, the system response are measured in each case. Comparing (a) with (b), it is known that the response of (a) is superior to (b). Fig 3.6 (a), (b), (c), (d) show the control voltage, gap, velocity, acceleration signal in this time.



(a) (b)



(c) (d)

Fig 3.6 Signals with guidance control
(a) Control Voltage (b) Air gap
(c) Velocity (d) Acceleration

3.3.2 Experiment for Plant II. (one vehicle)

- Specification of Plant II

Load	Weight	500 [kg]
Magnet	Length	0.6 [m]
Magnet	Weight	77 [kg]
Nominal	Current	25 [A]
Coil	Resistance	0.745[Ω]
Coil	Inductance	0.3 [H]
Number of turns		440[turns]
Nominal	Gap	10 [mm]

The method of experiment in this plant is as follows. First, in the state done the only suspension control, the lateral disturbances are put and then, the system response are monitored.After 2.5sec elapse, suspension & guidance Control is done and the lateral disturbance of the same magnitude as the first case are put, then the system responses are monitored, too. From Fig 3.7, it is shown that the better response against the lateral disturbance is obtained with guidance control.

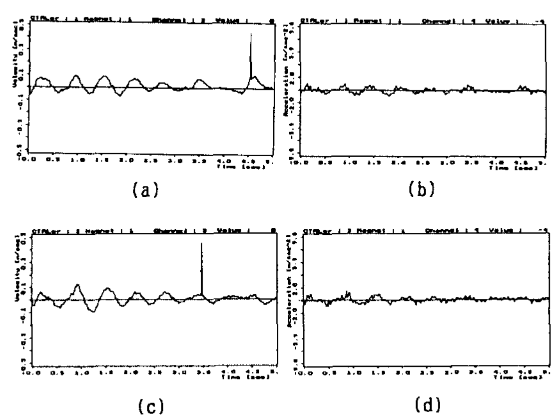


Fig 3.7 Waveforms in conditions
- with only suspension control at initial time, both suspension and guidance control after 2.5 sec
(a) leteral velocity of left magnet in one module
(b) leteral acceleration of left magnet in one module
(c) leteral velocity of right magnet in one module
(d) leteral acceleration of right magnet in one module

4. Observer design for flexible system

As mentioned in section 1, the difference between integration of acceleration and differentiation of clearance makes us consider guidance dynamics in depth. Acceleration signal contributes in improving ride guality in the rigid body system. But the use of absolute velocity, integration of acceleration, is found not fit well for flexible body system.

This section is concerned with designing a kind of observer which can be used for flexible guideway system as well as rigid guideway [6].

4.1 Design concept

The block diagram for the observer is shown in Fig 4.1.

The input signals to the observer are gap signal and accelerometer signal. The acceleration signal is passed through high pass filter with a suitable cut off frequency to remove the offset of acceleration signal.

The filtered acceleration signal is double intergrated by using the pure integrator with suitably chosen integration time and then this estimated position signal is compared to airgap signal to get the information for the rail dynamics.

This error means the track irregularities such as grades, sinusoidal vibration and etc. are fed-back to correct the accelaration and velocity signal.

So the estimated acceleration and velocity signals consist of absolute part caused by accelerometer and correction signal caused by gap sensor output. Two correction factors Koa and Kov are adjusted for the adequate observer dynamics. The constant Koa is for the stiffness and Kov is for the damping.

The primary aim in the state observer is to follow the estimated output to actual system output. If correction factors Kov, Koa are very large, the estimated position Z can follow the actual gap quickly. But if the disturbance input happens, this error quantity is amplified by large feedback gains Kov, Koa and make observer unstable. So the adequate correction factors have to be chosen through simulation and experiment. Physically, position signal has a 90 degree phase lag from velocity and also velocity has a 90 degree phase lag from acceleration.

Although vibrations occur in both magnet and rail as well as in only magnet, the velocity must have a 90 degree phase lead to airgap.

Now the physical meaning of each node of the observer is considered. The characteristic equation of the observer is as follows :

$$\Delta(s) = T_i^2 s^2 + K_{ov} T_i s + K_{oa} \qquad (4.1)$$

The two characteristic poles s1, s2 of the above equation can be obtained when $\Delta(s) = 0$

$$S_{1,2} = \frac{-K_{ov} \pm \sqrt{K_{ov}^2 - 4K_{oa}}}{2T_i} \qquad (4.2)$$

In fig 4.1, the estimated acceleration Z is given by

$$\hat{\ddot{Z}} = \frac{\left[\frac{T_{HPS}}{T_{HPS}+1}\right]\left[1 + \frac{K_{ov}}{T_i s}\right] T_i^2 \ddot{Z}_m + K_{oa} T_i^2 \ddot{Z}_c}{\Delta(s)} \qquad (4.3)$$

In the above equation, if the high pass filter is neglected

$$\hat{\ddot{Z}} \simeq \frac{S^2 T_i^2 \ddot{Z}_m + T_i K_{ov} S Z_m + K_{oa} T_i^2 Z_c}{\Delta(s)} \qquad (4.4)$$

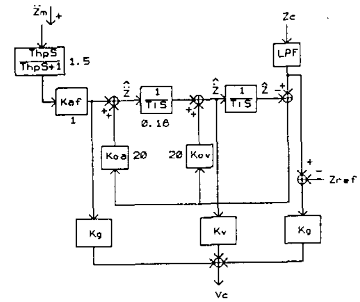


Fig 4.1 Block diagram for the reduced order observer

So the estimated acceleration signal Z is function of relative acceleration Z as well as absolute acceleration. This means that acceleration term of disturbance can be estimated by Z signal.

In equation (4.4), if no track disturbance happens, Z is converged to Zm approximately.

Also the estimated position Z is converged to gap signal and if integral constant is 1 [sec], the numerator and denominator can be cancelled approximately.

The equation for mode ② is given by

$$② = \frac{1}{T_i S} \hat{\ddot{Z}}$$

$$= \frac{(T_i S^2 + K_{ov} S)\dot{Z}_m + T_i K_{oa} \dot{Z}_c}{\Delta(s)} \qquad (4.5)$$

$$= G_{HV1} \dot{Z}_m + G_{CV1} \dot{Z}_c$$

For eq. (4.5) the signal which is obtained by integration of the estimated acceleration can be divided into two components like the estimated acceleration. The one is absolute velocity passed through high pass filter GLV1 and relative velocity passed through low pass filter GLV1.

So the weighting that is depending on frequency and Ti, Koa, Kov, can be adjusted to give good ride quality and stability margin with trade-off.

The estimated velocity Z is expressed as

$$\hat{\dot{Z}} = \frac{T_i S^2 \dot{Z}_m}{\Delta(s)} + \frac{K_{oa} T_i + T_i^2 K_{ov} S}{\Delta(s)} \dot{Z}_c \qquad (4.6)$$

$$= G_{HV2} \dot{Z}_m + Z_{cv2} \dot{Z}_c$$

For eq. (4.6), Z is also function of $\dot{Z}_m$ and $\dot{Z}_c$. The diffrence between eq.(4.5) and eq. (4.6) is the orders of numerator and denominator of two filters. For eq. (4.6), the numerator order of LPF for the relative velocity is 1. This means that since velocity is focused on relative velocity because of stability margin, the flexibility of filter design for LPF is needed. So this estimated velocity is chosen as feedback signal.

The weighting for relative velocity can be increased by increasing correction factors Kov, Koa. The equation for the estimated position is given by

$$\hat{Z} = \frac{S^2 Z_m + (K_{ov} T_i S + K_{oa}) Z_c}{\Delta(s)} \qquad (4.7)$$

For the above equation, if no track dynamics happens, Zm and Zc are same. So the numerator and denominator are cancelled approximately.

The estimaton error e is as follows :

$$e = Zc - Z = \frac{Ti^2 \ddot{Zc} - \ddot{Zm}}{\Delta (s)}$$

So the error econtains the acceleration term of Zc and Zm passed through second order low pass filter. Of course, the error means the track dynamics Zt passed through LPF.

4.2 Levitation simulation with reduced order observer

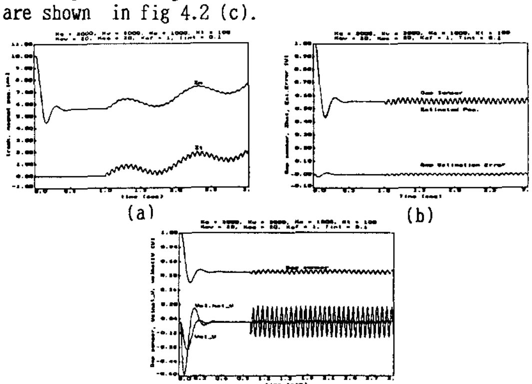
In this section 4.2, the levitation simulation with reduced order state observer for 9kg magnet which is in the control lab in KERI is carried out by using C language with IBM - PC AT 386.
The specification of 9kg magnet is as follows :

Length = 0.044 [m]
Width = 0.035 [m]
Resistance = 10.5 [Ω]
Nom. Induct. = 0.77 [H]
Turns of coil = 2000
Input Voltage = 70 [V]

To describe the actual test rig, the digital controller is simulated in discrete time and the magnet system is computed in continuous time.
Also the simulation parameter of the state observer is given by

Koa = 20
Kov = 20
Tint = 0.1 [sec]
Kaf = 1

Fig 4.2 shows the simulation results in case of that the state observer is used.
In Fig 4.2 (a), the absolute position of the magnet and track disturbance are plotted. The track disturbance is a ramp function of slope 0.001 [m/sec] in addition to 0.001 sin $(2\pi t)$ + 0.0003 sin $(30\pi t)$ at 1 [sec].
As a result, while the magnet follows the low frequency component of track disturbance, the high frequency part of disturbance is attenuated.
The actual gap and the estimated gap signal are compared in fig 4.2 (b). Due to adequate correction factors Koa,Kov, the estimated signal follows actual signal very well. The esimation error is decayed very soon. Also gap,the estimated velocity and the another velocity by integration of the estimated acceleration are shown in fig 4.2 (c).



(a) (b) (c)

Fig 4.2 (a) magnet position and track input reponse with the observer
(b) gap sensor,estimated position and estimation error
(c) gap sensor,estimated velocity and node ② signal in observer

From this figure, the estimated velocity has a 90 degree phase lead to gap signal ①. This is caused by small weighting for the relative velocity.This problem can be solved by increasing the weighting for the relative term. Until now, the simulation results when the observer is used are shown.
The another simulation that feedback the only absolute velocity when track input happens, is plotted in fig 4.3.

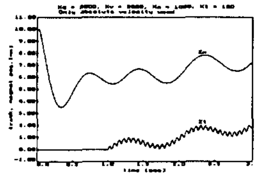


Fig 4.3 magnet position and track input with only absolute velocity feedback

Although the high frequency track input happens,the magnet does not almost vibrate, but follow the track grade of low frequency with large magnitude.This means that good ride quality can be obtained, but the stability margin is reduced.

4.3 Experiments

In this section,the experiments with the state observer are carried out. The observer is implemented with the analog operational amplifier TL084. first, to test the each states of the state observer, a simple action is carried out. By swing the magnet vertically, the estimated gap and the actual airgap are shown in fig 4.4. As shown in simulation results before, the estimated gap follows the actual airgap with very small error. Also, the estimated velocity and the actual airgap are shown in fig 4.5 at the same time.
The estimated velocity has a 90 degree phase lead to airgap correctly.So the satisfied results are obtained by the simple test. With the above test results, the levitation experiments for 9kg magnet are carried out.
Fig 4.6 shows that at the nominal airgap of 5mm, the reference airgap changed with ±2mm magnitude and 1Hz. As a result, the magnet can follow the reference airgap very well.

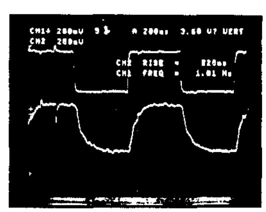


Fig 4.4 gap sensor and estimated position waveform

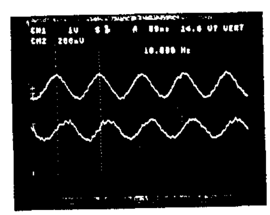


Fig 4.5 gap sensor and estimated velocity waveform

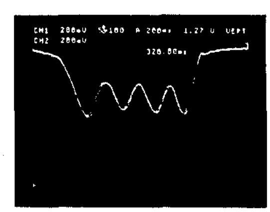


Fig 4.6 reference airgap and gap sensor

Finally to get the frequency response for the output to input of levition system, the Control System Analyzer (C.S.A, model Hewlett Packard 3563A) is used.
The sweeping frequency range is 0.1Hz to 100Hz and the magnitude of swept sine wave is ±0.1[V] (±1mm).
As a result, we can find the natural frequency of primary suspension system is about 11[Hz] as shown in Fig 4.7.

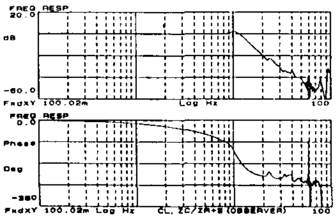


Fig 4.7 Frequency response for gap sensor vs. reference airgap

This means the above primary suspension system is very stiff.
So, with the more simulations and experiments, this natural frequency must be reduced to 6 ~ 10Hz.

5. Conclusion

In controlling attraction - type levitation system, active guidance control design based on the linearized model shows quite better result than passive guidance control. We showed the improved points not only by simulation but also by experiments. Also a concept of observer which contains absolute as well as relative velocity and gap imformation is applied in the levitation control design.

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