Consideration of the Non-linearity of Electromagnet for Dynamic Simulation

Jong-Boo Han, Hyung-Suk Han, Ki-Jung Kim and Chang-Hyun Kimm
Korea Institute of Machinery and Meterials Dept. of Magnetic Levitation and Linear Drive, Daejeon 305-343, KOREA
jbhan@kimm.re.kr, hshan@kimm.re.kr, kkj74@kimm.re.kr, chkim78@kimm.re.kr

Byung-Gwan Kang
Hyundai Rotem Company, Sam-Dong,Uiwang-Si, GyeongGi-Do, 462-18, KOREA
bgkang12@hyundai-rotem.co.kr

ABSTRACT: The attraction force of electromagnet dependent both on current and air gap is nonlinear. The consideration of the nonlinearity is needed in dynamic simulations for predicting air gap. To model the nonlinear attraction force, the experiment of the force is performed. The measured force is represented by 3D interpolation to be used in calculating the levitation force at each simulation step. Using the proposed nonlinear force model, dynamic responses are predicted.

1 INTRODUCTION

For an EMS-type Maglev vehicle, the levitation force is actively controlled by changing the voltage of electromagnet to maintain the air gap within an allowable range. Actually, the levitation force of an electromagnet is a non-linear function of current and air gap, and shows a saturation point beyond which it cannot increase when it reaches a high level. Therefore, a dynamics analysis of the Maglev vehicle that considers non-linear characteristics is needed to predict running stability. However, in preceding studies, the linear model, which may be obtained by using linear approximations of the levitation force for excursions around the nominal equilibrium point, has been used. In this paper, the relationship between the measured non-linear characteristics of levitation and guidance force and independent variables of current and air gap is processed by the interpolation method resulting 3-dimensional spline surface. By using this method, a non-linear levitation model was developed. With the proposed model, the vertical and lateral air gap simulation could be carried out to predict the dynamic behavior through the comparison between linear and nonlinear model.

Figure1. Maglev vehicle

2 MODELING

2.1 *Model of Maglev vehicle*

For the simulation, the model of Maglev vehicle is created in a normal manner in the multibody dynamics field. The resulting model is shown in figure 2. As stated in the previous section, all calculations and tasks required for the electromagnet are processed in the user-defined subroutine. The bogie consist of 2 side frame, 4 anti-roll beams, 2 linear induction motors, 4 air spring, and 2 traction rods.

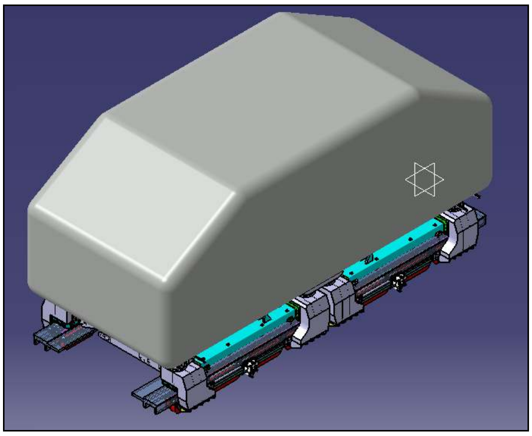

Figure2. Maglev vehicle multibody model

2.2 *Linear electromagnet force*

To predict more accurate, a nonlinear levitation force model would be required, but a reasonably accurate linear model may be obtained by using linear approximations of the force for excursions around the nominal equilibrium point (i_0, c_0) as shown in figure 3.

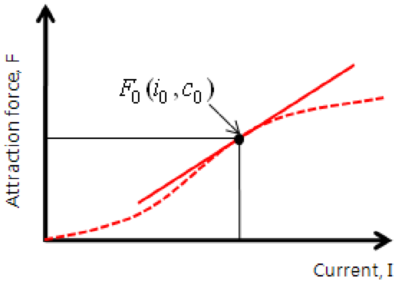

Figure3. Linear approximation of electromagnet force

Using these linear approximations, the changes in the levitation force and the current are expressed as Equations 1 and 2, respectively when lateral airgap is zero.

$$F(\Delta c(t), \Delta i(t)) = k_c \Delta c(t) - k_i \Delta i(t) \tag{1}$$

$$\Delta \dot{i}(t) = \frac{k_c}{k_i}\Delta \dot{c}(t) - \frac{R}{L_0}\Delta i(t) + \frac{1}{L_0}\Delta v(t) \tag{2}$$

where,

$$L_0 = \frac{\mu_0 N^2 A}{2c_0}$$

$$k_i = \frac{\mu_0 N^2 A i_0}{2c_0^2}$$

$$k_c = \frac{\mu_0 N^2 A i_0^2}{2c_0^3}$$

F : Levitation force,
A : Section area of magnet (m^2),
μ_0 : Permeability factor,
N : Number of turn of magnet coil (turn),
i_0 : Nominal current (A),
c_0 : Nominal air gap (m),
c : Air gap (m),
v : Voltage (V),
R : Resistance (Ω).

If the lateral air gap of the electromagnet from the guiderail is represented by $d(t) \neq 0$, then the levitation and guidance forces may be expressed as

$$F_y = F_0 \times \left[-\frac{2c(t)}{\pi \omega_m} \tan^{-1}\left(\frac{c(t)}{d(t)}\right) \right] \tag{3}$$

$$F_z = F_0 \times \left[1 + \frac{2c(t)}{\pi \omega_m} + \frac{2d(t)}{\pi \omega_m} \tan^{-1}\left(\frac{c(t)}{d(t)}\right) \right] \tag{4}$$

where,

F_z : Levitation force,

F_y : Guidance force,

d : Lateral air gap (m),

c : Air gap (m),

w_m : Magnet width (m).

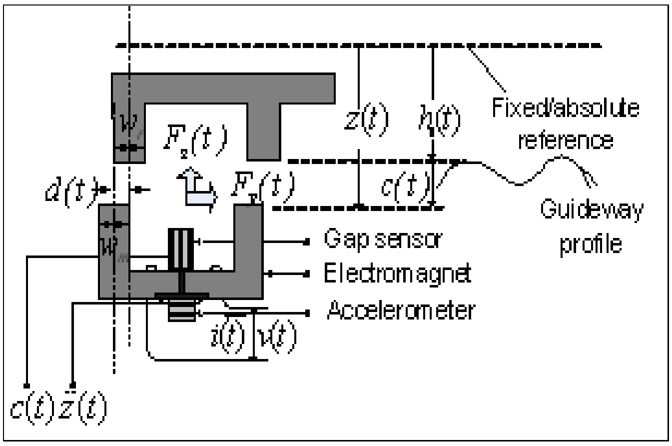

Figure3. Principle of the electromagnet

2.3 *Nonlinear electromagnet force*

Dynamic performance simulation of Maglev vehicle with the linear electromagnet model could be obtained the different results by saturation of electromagnet force. If maglev vehicle run on the guideway, ideal electromagnet force can increase more and more for stability the air gap. But nonlinear electromagnet force cannot increase continuously by saturation state of electromagnet force. Therefore, it is necessary to evaluate the linear model through the comparison of dynamics behavior using linear and nonlinear model.

First of all, a measurement of electromagnet force is carried out to know the characteristic curve of the nonlinear force as shown in figure 4 by ROTEM Company. It is considered the range of vertical airgap 6 to 14mm and lateral airgap 0 to 15mm as gradually increasing the current at 0 to 55A.

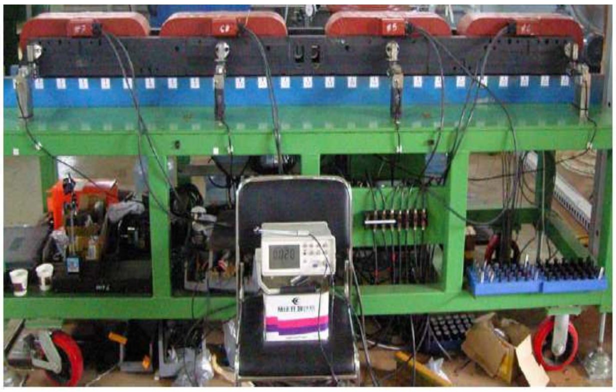

Figure4. Test for electromagnet force

Consequently, characteristics curve of nonlinear electromagnet force are obtained. Figure 5 shows the deviation of electromagnet force, as increasing current at air gap of 6mm, 8mm, 10mm and 12mm, respectively. The results of them, electromagnet force is observed in the point nominally air gap 10mm that it could be saturated around 60KN.

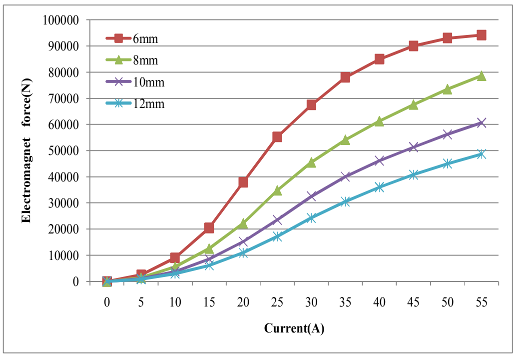

Figure5. Experiment results of electromagnet force

To apply the nonlinear electromagnet model which is composed of two independent variables in the simulation, 3-dimensional spline surface interpolation method is used as shown in figure 6.

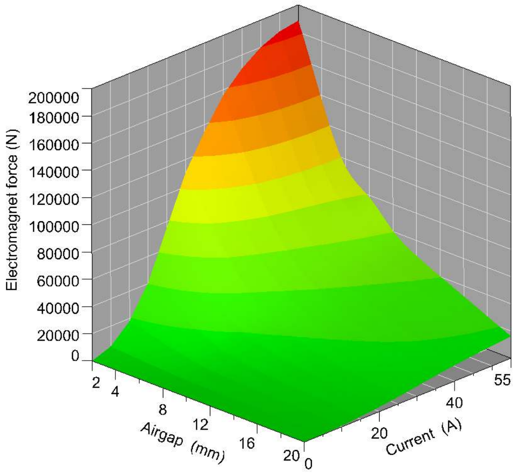

Figure6. Spline surface of electromagnet force

2.4 *Guideway*

A curved guideway is composed of tangent, clothoid curve, and circular curve section. The minimum length of the transition curve is mainly limited by the allowed superelevation gradient, which is determined by the mechanical decoupling tolerance. The 60m-length clothoid transition segment and 48 cant angle is arranged for the 800m-radius curve at the speed of 80km/h as shown table 1. Based on the above-mentioned curved guideway, the simulation for curving performance is carried out.

Table 1 Simulation conditions

Vehicle velocity (km/h)	80
Tangent section (m)	370
Clothoid curve (m)	60
Circular curve radius (m)	800
Cant (deg)	4
Guideway deflection(mm)	(Max.) 12
Surface roughness(mm)	(Peak) ±5

3 SIMULATION

3.1 *Tangent section*

The results obtained from the air gap simulation, are presented in figure 8 and 9. Those of figure 8 and 9 show the air gap time-histories to compare linear model with nonlinear model. In the figure 8, vertical air gap which is criterion of levitation stability is almost the same as shown in figure8. But lateral air gap which plays an important role in curving performance is somewhat different as shown in figure9. When nonlinear model is used, peak value of lateral air gaps is lower than them of linear model. It is said that the nonlinear model is more stable in the tangent section.

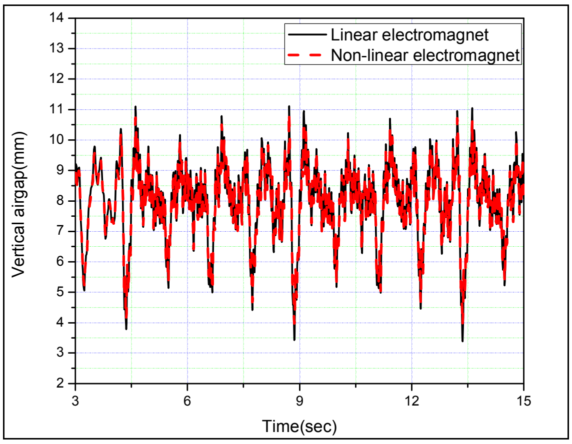

Figure8. Vertical airgap at linear section (80km/h)

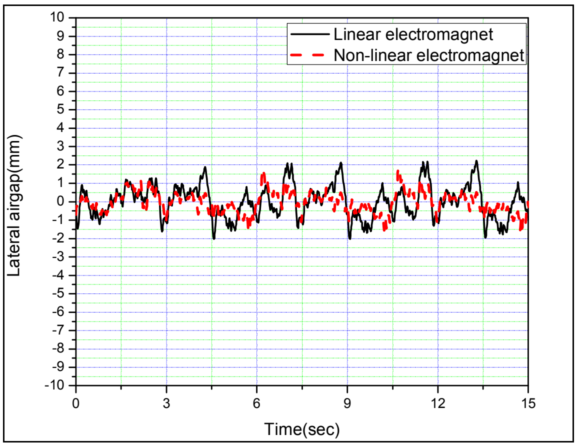

Figure9. Lateral airgap at linear section (80km/h)

3.2 Circular curve section

Figure 10 and 11 show results of curving performance simulation. In figure 10, peak value of vertical air gap is almost same with 11mm and 10.5mm, respectively. But lateral air gap is different between two models. With nonlinear model, the deviation of lateral air gap is within the range of -1.7 to 2.5mm. When linear model is used, lateral air gap is controlled at -4mm to 4mm.

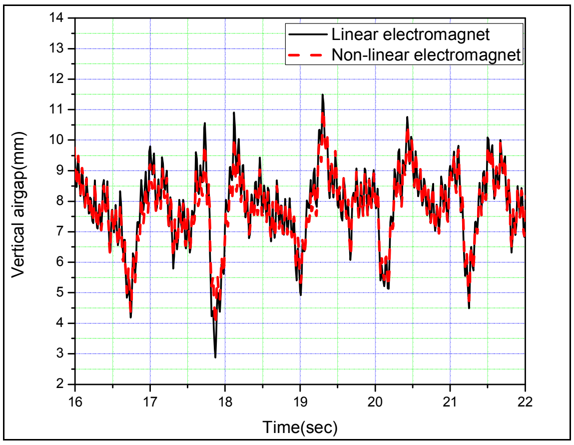

Figure10. Vertical airgap at curve section (80km/h)

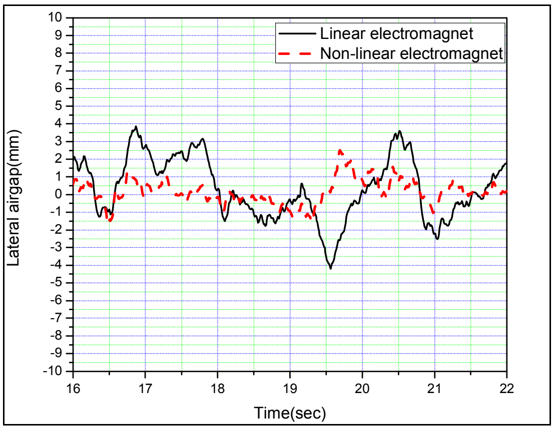

Figure11. Lateral airgap at curve section (80km/h)

4 CONCLUSIONS

In this paper, 3-d multibody dynamics of Maglev vehicle considering the linear and nonlinear electromagnet is proposed, respectively. Analysis of running performance is carried out in order to evaluate the linear model through comparison with proposed model. In the inference from simulation results, levitation force is almost the same using two models at tangent and curved guideway. But guidance force is the rather difference between two models through comparison with the lateral air gap in particularly curved guideway. Nevertheless, all the air gaps of two models are maintained within all allowable range. Therefore, it would be fine to use the reasonable linear model. And, it is more efficient in the point of simulation time.

5 REFERENCES

Yim B.H., Han H.S., Lee, J.K., and Kim S.S., Curving performance simulation of an EMS-type Maglev vehicle, *Vehicle System Dynamics*, Vol. 47, No. 10, pp. 1287-1304, 2009.

Lee J.S., Lim D.J., and Kim M.Y., Moving urban Maglev-vehicle analysis considering non- linear magnetic levitational force effect, COSEIK, 2009.

Coenraad E., *Modern railway track second edition*, C. Esveld, Netherlands, 2001.

Shabana A.A., *Railroad vehicle dynamics: A computational approach*, Taylor & Francis Group, USA, 2007.

Yim B.H., and Han H.S., Curve negotiation analysis of a Maglev vehicle utilizing electromagnetic suspension system, Asian Conference on Multibody Dynamics, 2008.

Sinha P.K., *Electromagnetic suspension dynamics & control*, Peter Peregrinus Ltd, London, United Kingdom, 1987.

Han H.S., A study on the dynamic modeling of a magnetic levitation vehicle, *JSME International*, Vol. 46, No. 4, pp. 1497-1501, 2003.