State-of-the-art Multibody Dynamic Simulations of EMS-type Maglev Vehicles at KIMM

No. 56
Hyungsuk Han, Seokjoon Moon and Hanwook Cho
KIMM, System Engineering Division, 305-343, Daejeon, Korea
hshan@kimm.re.kr, sjmoon@kimm.re.kr, hwcho@kimm.re.kr
Namjin Lee
Bogie Development Team, Hyundai Rotem Company, 437-718, Uiwang, Korea
njlee@hyundai-rotem.co.kr

ABSTRACT: Vehicle dynamics is a link between the guideway and the maglev vehicle components, and for this reason it is an essential area of study in the development of a commercial maglev system. KIMM, a leading maglev vehicle institute in Korea, has developed dynamics simulation techniques and programs to predict the dynamic responses of existing maglev vehicles and those of new maglev vehicles under development. The advances in modelling and simulation techniques proposed by KIMM are dynamic simulations of EMS maglev vehicles based on virtual prototyping. As a result of this approach, it might be expected that such simulations could provide an abundance of information for maglev designers. In this paper, state-of-the-art multibody dynamic simulation approaches and their applications are introduced. Dynamic responses such as ride quality, curve negotiation, and air gap variation are simulated. In addition, critical areas for future research are identified.

1 INTRODUCTION

The dynamic response of an EMS (Electromagnetic suspension)-type maglev vehicle has important consequences for safety and ride quality, guideway design, and system costs [10]. In particular, when establishing the guideway design requirements, the trade-offs between guideway design and vehicle suspension system must be considered if maglev vehicle systems are to be economically feasible. To do this, a more comprehensive or detailed model that considers the dynamic interactions between vehicle and guideway is necessary in the early design stage. Though vehicle dynamics has been an area of study for many researchers, only a few full-vehicle multibody dynamic simulations, based on virtual prototyping, can be found in the literature [2].

KIMM, a leading maglev vehicle institute in Korea, has developed dynamics simulation techniques and programs for predicting the dynamic responses of existing EMS-type maglev vehicles and new EMS-type maglev vehicles under development. The advances in modelling and simulation techniques proposed by KIMM are dynamic simulations of EMS-type maglev vehicles based on virtual prototyping. As a result of this approach, it might be expected that the simulation proposed here could provide an abundance of realistic dynamic responses for maglev designers. In the paper, the state-of-the-art multibody dynamic simulation approaches and their applications are introduced. Dynamic characteristics such as ride quality, curve negotiation, and air gap variation are demonstrated. In addition, critical areas for future research are identified.

2 MODEL

2.1 Modeling Concept

The maglev simulation team of KIMM uses LMS Virtual.Lab Motion Software, a multibody dynamic simulation program, to produce a "virtual prototype," realistically simulating on their computers the full-motion behavior of EMS-type maglev vehicles [5].

With LMS Virtual.Lab Motion Software, users can quickly explore multiple design variations, testing and refining their designs until system performance is optimized. This can help reduce the number of physical prototypes required, improve design quality, and dramatically shorten product development cycles. The data exchanges between the engineering softwares are illustrated in Figure 1. The modeling data and simulation results can be automatically imported and exported between the engineering softwares.

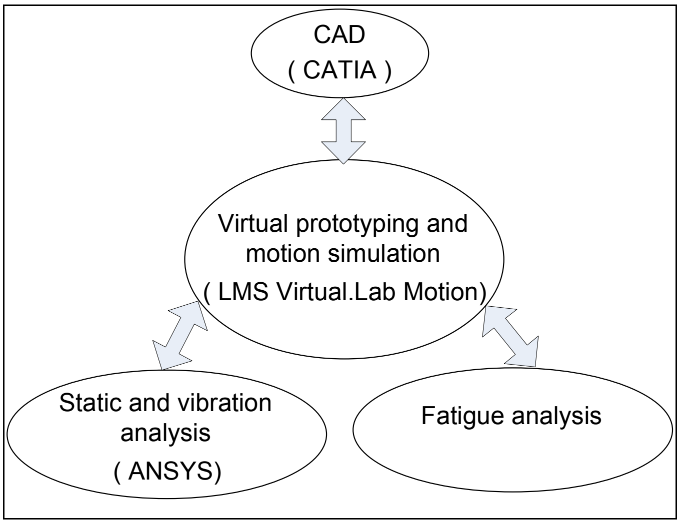

Figure 1. Data exchanges between engineering softwares.

2.2 *Electromagnet*

Figure 2 illustrates the principle of EMS-type suspension. The levitation force $F_z(t)$, or lift force, and guidance force $F_y(t)$ are functions of the air gap, $c(t)$, lateral air gap, or displacement, $d(t)$, and current $i(t)$. To define both of the forces, the idle levitation force $F_0(t)$ is first defined when $d(t)=0$ [7]. A reasonably accurate linear model may be obtained by using linear approximations of the idle levitation force around the nominal equilibrium point (i_0, c_0):

$$F_0(\Delta c(t), \Delta i(t)) = k_c \Delta c(t) - k_i \Delta i(t) + F_{static} \quad (1)$$

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

where,

$$L_0 = \frac{\mu_0 N^2 A}{2c_0}, \quad k_i = \frac{\mu_0 N^2 A i_0}{2{c_0}^2}, \quad k_c = \frac{\mu_0 N^2 A {i_0}^2}{2{c_0}^3},$$

F_{static}: Static force (N),

F_0: Idle levitation force (N),

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 between the electromagnet and the guiderail is represented by $d(t) \neq 0$, then the levitation and guidance forces may be expressed as [7].

$$F_z = F_0 \times \left[1 + \frac{2c(t)}{\pi w_m} + \frac{2d(t)}{\pi w_m} \tan^{-1}\left(\frac{c(t)}{d(t)} \right) \right] \quad (3)$$

$$F_y = F_0 \times \left(-\frac{2c(t)}{\pi w_m} \tan^{-1}\left(\frac{d(t)}{c(t)} \right) \right) \quad (4)$$

where,

F_y : Guidance force (N),

F_z: Levitation force (N),

d : Lateral air gap (m),

c : Air gap (m),

w_m : Magnet width (m).

In determining both forces with Equations (1) to (4), the $c(t)$, $\dot{c}(t)$, $d(t)$ must be calculated from the position and velocity of the pair of bodies. To more accurately calculate the levitation and guidance forces in consideration of the relative position and orientation, the electromagnet's pole face is piecewised along the length of the pole face, as shown in Figure 3. After calculating F_{z_i} and F_{y_i} of each segment, they are summed into the total levitation and guidance forces F_z and F_y on one electromagnet, and the two forces are applied to both the electromagnet and the guideway.

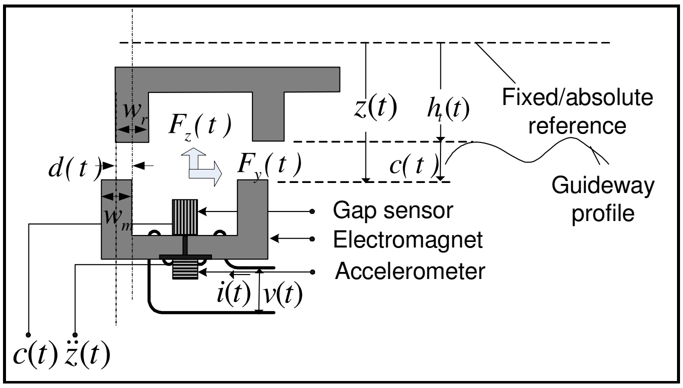

Figure 2. Principle of electromagnetic suspension.

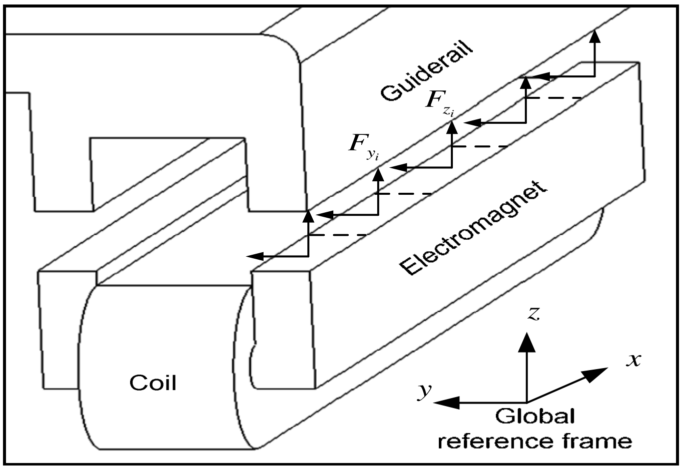

Figure 3. Piecewised levitation & guidance forces.

2.3 *Full Vehicle*

The UTM-02 in Figure 4 is a typical EMS-type maglev vehicle that is used only for urban transit, running at relatively low speeds of less than 100 km/h. Each car has 3 bogies, and each bogie consists of 4 frames, 4 revolute joints between frames, 2 air springs, 4 dampers, and 2 traction rods with rubbers in their holes. 8 electromagnets are attached to the side frames for levitation and guidance. Each module consisting of two electromagnets on a corner is independently controlled by changing the voltage in its winding. Two cars are coupled with a conventional coupler. Figure 5 shows the full vehicle multibody dynamic model created for the UTM-02, an EMS-type maglev vehicle. The model is defined as follows:

Table 1. Model for the UTM-02.

Element	Number
Bodies	88
Revolute joints	18
Spherical joints	48
Cylindrical joints	30
Air springs	12
Traction rod bushings	8
Dampers	24
Degrees-of -freedom	162

Figure 4. Urban maglev vehicle UTM-02 running over a flexible guideway.

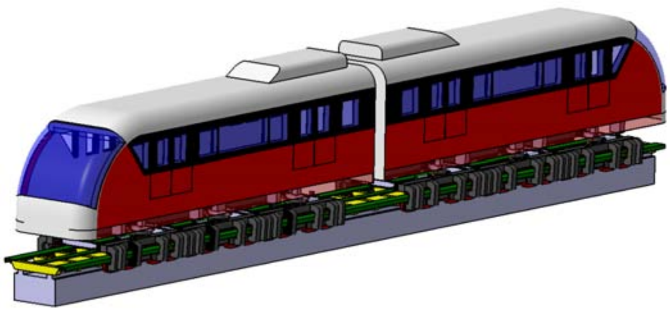

Figure 5. Full vehicle multibody dynamic model for the UTM-02.

2.4 *Rigid Vehicle/Rigid Guideway*

Though it is desirable to consider all components as flexible bodies, occasionally a rigid body model is efficient, such as, for example, to evaluate ride quality before the detailed guideway design is finished. In this model, the guideway elevation is assumed to have a stationary profile. That is, the vehicle runs over a pre-deformed guideway. The model, as shown in Figure 5, is particularly suited to establishing the guideway design requirements, such as mid-span deflection limit, surface roughness, and construction tolerances [1,3].

2.5 *Rigid Vehicle/Flexible Guideway*

To more accurately analyze the dynamic interactions between the vehicle and the flexible guideway, the guideway must be modeled as a flexible body. This model can simulate the resonance between the maglev vehicle and the guideway, from which the guideway's vibrational design specifications, such as natural frequency, mass density, rigidity, and damping, can be established. Moreover, levitation stability, guideway behavior, and dynamic load to the guideway can be analyzed. A flow and structure of the technique employing flexible multibody dynamics is shown in Figure 6. Equations of motion of a constrained system with a flexible body and its features are presented in references [8-9]. Vibration and static correction modes from a finite element code, which is shown in Figure 7, are used to account for the linear elastic deformation of flexible bodies. This theory has already been incorporated into some general-purpose spatial dynamics codes. The study uses LMS Virtual.Lab Motion as a dynamic analysis code for generating equations of motion and solving them [5]. The elevated guideway is modeled as a flexible body through modal superposition. ANSYS is used for carrying out both vibrational and static analysis, interfacing with LMS Virtual.Lab Motion. The important matters addressed in the modeling and simulation process shown in Figure 6 are as follows:

- LMS Virtual.Lab Motion performs the modeling of bodies and their geometries, joints, suspensions, and levitation control systems, and specifies the initial conditions of dynamic simulation. The equations of motion of the system are then integrated in the program using a variable-step, variable-order numerical integration algorithm.
- Equations of the magnetically-levitated system that will be given in the next section are defined in the user-defined subroutine of LMS Virtual.Lab Motion. The user-defined subroutine senses the air gap, which is the distance between the electromagnet and the flexible guideway, its derivative, and the absolute vertical acceleration of the electromagnet. The subroutine then evaluates the system of differential equations of the levitation system, and calculates the levitation forces. The forces are applied to both the electromagnet and the guideway in the subroutine.
- The ANSYS software is used to create finite element models for the guideway, and carry out both vibrational and static analysis. Boundary conditions for vibration and static correction mode analysis must be properly chosen in order for gross motion and local deformation modes in operation to be considered in the analysis. Here, the boundary conditions and load cases are automatically generated from LMS Virtual.Lab Motion in ANSYS format.

Figure 8 shows the rigid vehicle/flexible guideway developed in the paper [4].

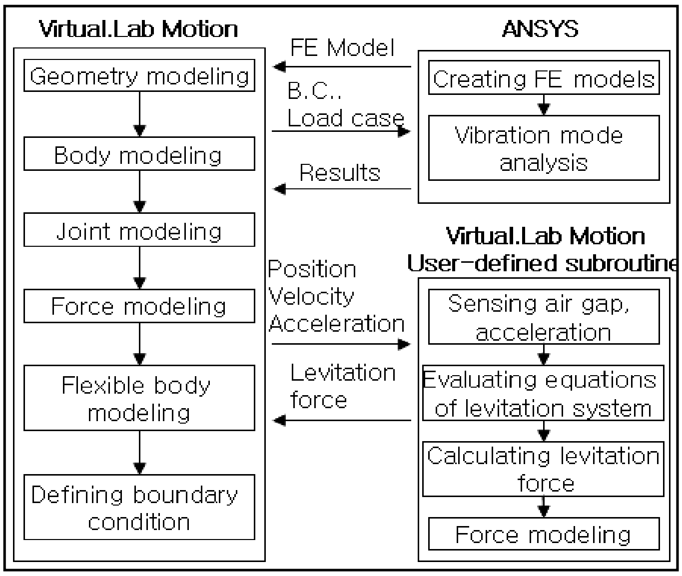

Figure 6. Modeling and simulation process of the rigid vehicle/flexible guideway model.

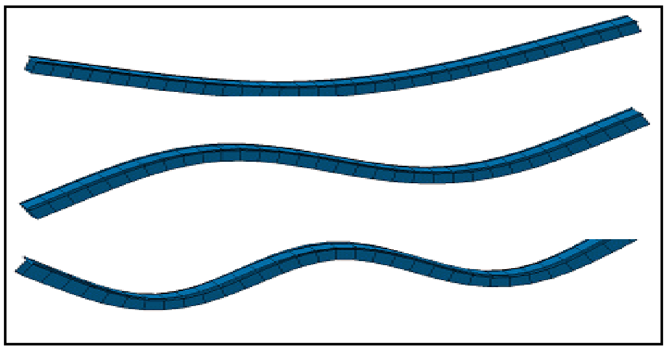

Figure 7. Vibration models of the guideway to be considered the coupled dynamic model.

2.6 *Flexible Vehicle/Rigid Guideway*

To investigate the effect of vehicle component flexibility on the levitation stability, or evaluate the durability of components such as bogie frame, the components must be modeled as flexible bodies. The modeling techniques are the same as those used in the rigid vehicle/flexible guideway model mentioned in the previous section. Figure 9 demonstrates the model created in the study. For numerical efficiency, only the leading bogie frame is modeled with a flexible body [6].

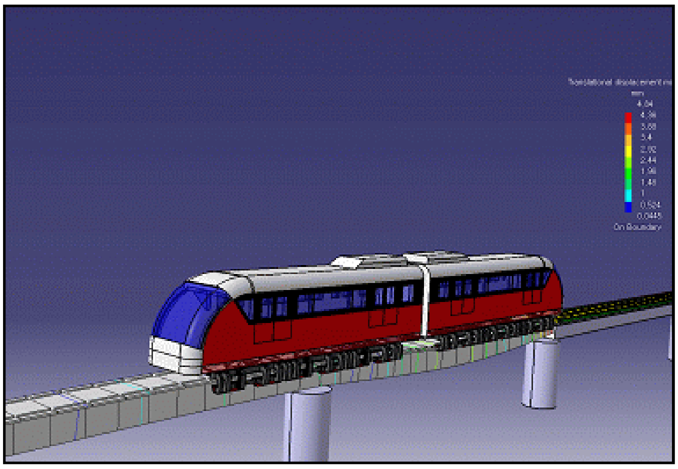

Figure 8. Rigid vehicle/flexible guideway model for the UTM-02.

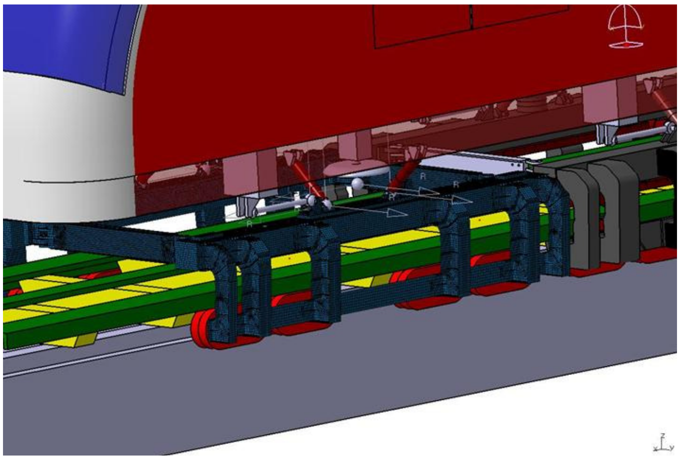

Figure 9. Flexible vehicle/rigid guideway model for the UTM-02.

2.7 *Flexible Vehicle/Flexible Guideway*

The most advanced dynamic model is when all the components comprising the maglev system are modeled as flexible bodies. This model allows us to provide the most comprehensive and realistic dynamic simulation. It can be said that this model well-represents the modeling concepts proposed here. However, this modeling process is just an extension of the one illustrated in Figure 6.

3 APPLICATIONS

3.1 *Air Gap*

In EMS-type maglev vehicles, the nominal air gap, which is the distance between the electromagnet and the guideway, is usually 8-10 mm. The air gap control system controls the voltage in the electromagnet to maintain air gap deviation within an allowable range, in order to avoid the mechanical contact of the electromagnet with the guideway. Figure 10 shows the air gap time histories on the leading bogie at a speed of 110 km/h, using the dynamic model mentioned above. The guideway mid-span deflection limit and surface roughness amplitude are assumed to be L(25)/2000 m and ±2 mm(C=2), respectively. With these air gap responses, the air gap control system could be optimized and improved at the design stage, without a physical prototype.

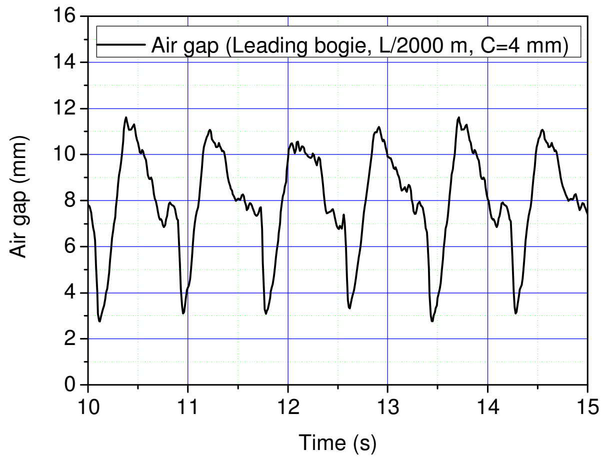

Figure 10. Example of air gap history.

3.2 *Ride Quality*

Ride quality can be also evaluated using the multibody dynamic model. An index of ride comfort, the UIC comfort index, is evaluated as presented in Table 2. The team has extensively simulated the ride quality with different guiderail surface roughness amplitudes and mid-span deflection limits, to enable the design of a guideway that provides an acceptable level of ride comfort.

Table 2. Example of ride quality, UIC comfort index.

Position	UIC comfort index	Evaluation
Frontal carbody floor	1.4	Good comfort
Middle carbody floor	1.0	Very good comfort
Rear carbody floor	0.9	Very good comfort

3.3 *Curve Negotiation*

If the lateral air gap exceeds an allowable range, contact could occur between the electromagnet and the guideway during curving. This mechanical contact may make the vehicle unstable. Therefore, a curve negotiation simulation of maglev vehicles is required in order to evaluate and enhance curving performance. Figure 11 shonws the maglev vehicle running on a curved guideway, and Figure 12 shows the lateral air gap response. It can be noted that the maximum lateral air gap deviation is approximately 5 mm, and thus mechanical contact with the guiderail is avoided. These simulation studies may be useful in designing a bogie mechanism and establishing the specifications for guideway profile.

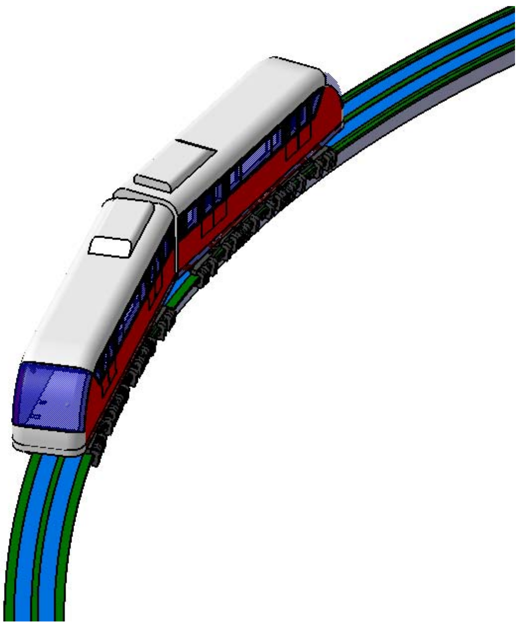

Figure 11. Animation of curving simulation.

3.4 *Guideway Design Requirements*

To lower guideway construction cost, guideway design requirements must be established, covering variables such as roughness, mass and stiffness. The dynamic simulation is also useful in determining these specifications.

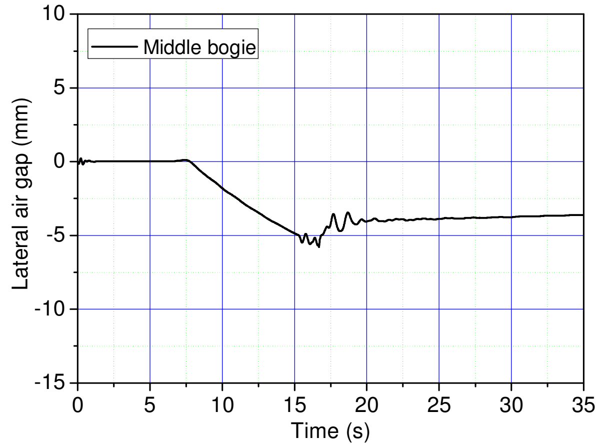

Figure 12. Example of lateral air gap history.

3.5 *Durability*

The simulation can predict the load histories of the bogie structure. With the load histories obtained, a fatigue analysis has been carried out. Figure 13 presents an example of fatigue analysis results. It can be seen that the lifespan requirement, 25 years, is satisfied.

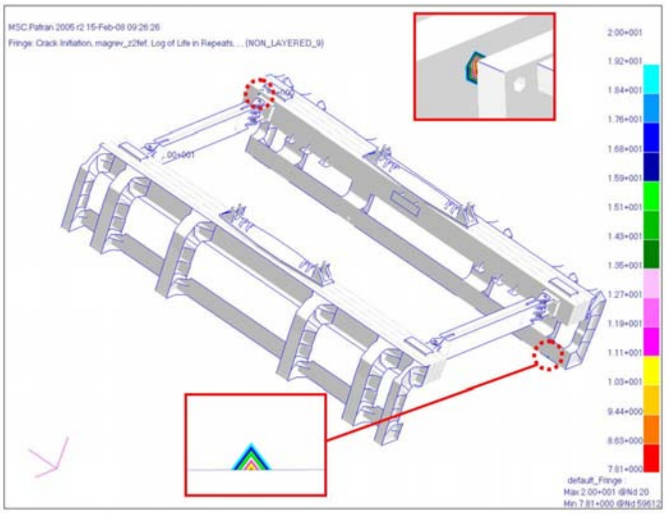

Figure 13. Example of fatigue analysis.

4 CONCLUSIONS

KIMM, a leading maglev vehicle institute in Korea, has developed dynamics simulation techniques based on virtual prototyping and programs for predicting the dynamic responses of EMS-type maglev vehicles. With the model, engineers can quickly explore multiple design variations, testing and refining their designs until system performance has been optimized. We have experienced the usefulness of this model in designing the urban maglev vehicle UTM-02 and new maglev vehicles under development. In addition, some critical areas for future research have been identified, which are as follows:

-develop an empirical electromagnet levitation and guidance force model to consider its nonlinearity

-model the carbody as a flexible body to represent its flexibility, which could affect ride quality and stability

-create a numerically efficient flexible guideway model

-include the dynamics of electrical equipment, such as chopper

-quantify guideway irregularities, such as steps at guiderail joint, surface roughness, and sleeper deflection.

5 REFERENCES

B.Y. Yim, H.S. Han, B.H. Kim, and S.S. Kim, "Curving Performance Simulation of an EMS-type Maglev Vehicle," Vehicle System Dynamics, To be published.

H.J. Hong and J.C. Wesen, "The Levitation Control Simulation of Maglev Bogie Based on the Virtual Prototyping Platform and MATLAB," Maglev2004, 2004.

H.S. Han, B.H. Yim, N.J. Lee, Y.J. Kim, and B.H. Kim, "Prediction of Ride Quality of a Maglev Vehicle Using a Full Vehicle Multi-body Dynamic Model," Vehicle System Dynamics, To be published.

H.S. Han, J.M. Lee, B.H. Kim, H.K. Sung, and K.J. Kim, "Dynamic Modeling of a Magnetically-levitated Vehicle Running over a Flexible Guideway," Multibody Dynamics 2007, ECCOMAS Thematic Conference, June 2007.

LMS Virtual.Lab Motion Users Manual, LMS International.

N.J. Lee, H.S. Han, S.W. Han, P.J. Gaede, "Evaluation of the Fatigue Life of Aluminum Bogie Structures for the Urban Maglev UTM-02," WCRR 2008, Seoul, May 2008.

P. K. Sinha, "Electromagnetic Suspension Dynamics & Controls," Peter Perefrinus, 1986.

W.S. Yoo and E.J. Haug, "Dynamics of Articulated Structures:Part I. Theory," J. Struct. Mech. Vol. 14, No.1, 105-126, 1986.

W.S. Woo and E.J. Haug, "Dynamics of Articulated Structures:Part II. Computer Implementation and Applications," J. Struct. Mech. Vol .14, No.2, 177-189, 1986.

Y. Cai and S.S. Chen, "A Review of Dynamic Characteristics of Magnetically Levitated Vehicle Systems," Argonne National Laboratory, Argonne, Illinois, 1995.