Fuzzy Controller Design with the Degree of Non-uniformity for the Scaled Active Steering Testbed in the Railway Vehicle

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Abstract: - In urban transit systems, rail passenger vehicles are often required to negotiate tight curves. Running curve railway, the wheelsets of conventional vehicles generally misalign radically with the track increasing wheel/rail contact forces and resulting in increased wheel and rail wear, outbreak of squeal noise, fuel consumption, and risk of derailment. To solve these problems, modified suspension system designs, application for alternate wheel profiles, active and semi-active steering techniques have been proposed. Active steering system has proven its ability to bridge the gap between stability and curve friendliness. This paper presents a technique for improving the performance of active steering fuzzy control systems by adequately changing the widths of triangular fuzzy membership functions. Experiment results show that the proposed fuzzy controller robustly yields good performance comparing with conventional controller.

Key-Words: - Fuzzy Controller, Degree of Nonuniformity, Active Steering, Railway Vehicle, Scaled Model

1 Introduction

Fuzzy set theory based on fuzzy controllers allows imprecise and qualitative information to be expressed in a quantitative manner. Over the year, fuzzy logic techniques have been applied to a wide range of control systems including railway vehicle control systems [1]~[4].

In urban transit systems, urban trains are often required to travel tight curves. During curve negotiation, the wheelsets of conventional vehicles generally misalign radically with the track increasing wheel/rail contact forces and resulting in increased wheel and rail wear, outbreak of squeal noise, fuel consumption, and risk of derailment. To alleviate these problems, modified suspension system designs, application for alternate wheel profiles, active and semi-active steering techniques have been proposed. Rail vehicles originally have self-steering ability on curved tracks, and this function is originated from the wheel conicity and rigid connection of two wheelsets by an axle. But this mechanism has two problems. One is a hunting phenomenon by a self-excited vibration of the wheelsets and the other is a curving ability by self-steering mechanism. To solve this problem and compromise between stability and curving performance, there are number of studies and developments such as passive, semi-active control, active control, independently rotating wheelsets (IRW), and so on [5]~[16]. Active steering system has proven its ability to bridge the gap between stability and curve friendliness [7]~[29]. This system consist of one actuator per wheelsets, sensors to detect wheel/rail displacement, sensors to detect track curvature, and a controller counter-balancing any track disturbance to avoid the development of a running instability and optimizing the wheelsets' alignment with regard to the track in curves according to the selected optimization scheme.

Generally scaled railway vehicles were developed to reproduce the fundamental dynamic behavior of the full size railway vehicle in laboratory conditions. In this paper, a 1/5 scaled railway vehicle is carried out for the development and testing of prototype bogie design, and the investigation of fundamental railway vehicle running behavior [30][35].

This paper describes the development of a fuzzy controller of an active steering control system of railway vehicle. Experiment results have been shown that the proposed fuzzy controller performed better than conventional controller. This paper is organized as follows. Section 2 describes an active steering

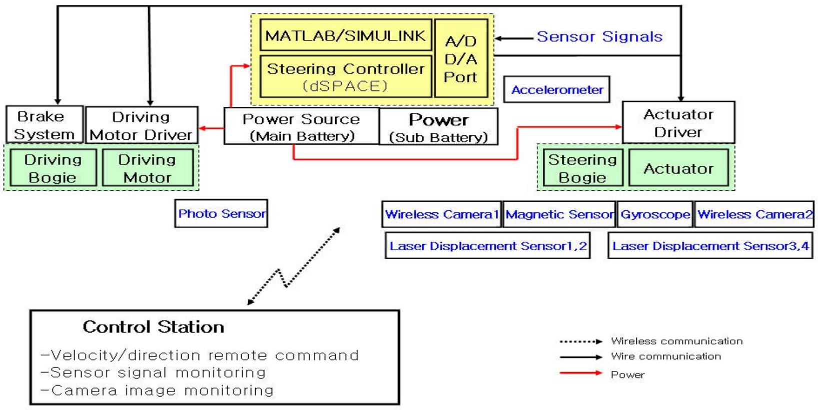


Fig.1 Block diagram of the active steering control system

control system for 1/5 scale model and Section 3 overviews the fuzzy controller design for active steering using the degree of nonuniformity of fuzzy membership function. Section 4 contains the experiment results. Finally, we close the paper with a brief conclusion in Section 5.

2 The Scaled Active Steering Testbed

Control strategy to the active steering system based on two axle vehicle attached to actuator of the yaw torque considering the riding quality has been applied. The testbed for the active steering bogie for curve running test consists of the control station module, steering controller module, power module, driving motor module, and various sensors module. Fig.1 shows the block diagram of the active steering control system.

Table 1 Active steering control systems of the active steering testbed

Module	Accomplishment Contents
Control Station	▪Remotely speed and the direction command transmission ▪ Steering controller signal monitoring ▪Wheel/rail contact image acquisition using wireless camera systems
Steering Controller	▪Generation of steering command to actuator based on the control algorithm ▪A/D and D/A input/output terminals ▪MATLAB/SIMULINK and dSPACE as a rapid control prototyper
Actuator	▪Creation of yaw moment corresponding to the control signals ▪Actuator displacement output
Sensor Systems	▪Wheel/rail relative displacement measurement ▪Carbody vibration characteristic measurement ▪Yaw angle measurement of the steering bogie ▪Detection of the curve information ▪Wheel/rail dynamics monitoring

2.1 The Steering Bogie

A schematic view of an F-link type steering bogie which consists of two steering actuators is depicted in Fig.2. The wheelsets are mounted on the bogies through the primary suspension and the vehicle body is supported by the secondary suspension. In the active solutions yaw actuators are located between the bogies and the corresponding wheelsets. Bogie frame is constructed by aluminum material.

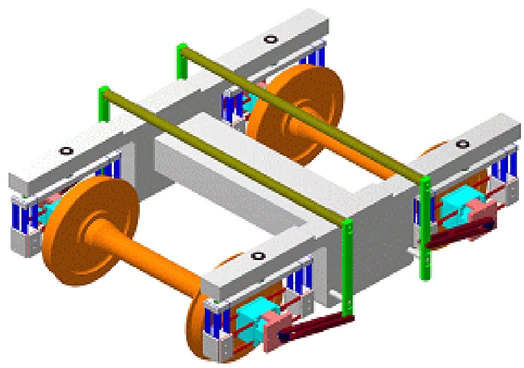


Fig.2 Schematic views of an active steering bogie

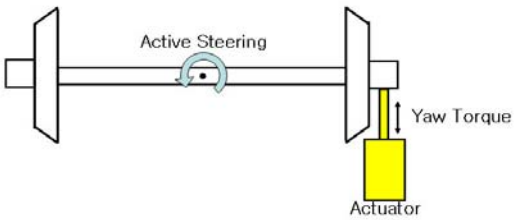


Fig.3 Active steering control strategy: apply a controlled torque to the wheelset in the yaw direction

2.2 Driving Bogie

Driving bogie module consists of a BLDC motor of DC 48[V] 39.1[A], a 5:1 reduction gear(worm geared type NMRV 050 model by MOTOVARIO Inc.), a driving motor driver, a braking system and connection panels. The rated output power of BLDC motor is 1.5[KW] and it rotates with 2000 [rpm] maximally. The motor driver is including the motor ON/OFF terminal, the velocity control terminal with 0[V]~5[V] and the direction selective terminal (0[V] and 5[V]). A photoelectric sensor which is mounted the wheel side of the driving motor axle is used for calculating the vehicle speed.

Table2 Specification of the BLDC motor

Rated Output Power	1500 [W]
Rated Input Voltage	DC 48 [V]
Max.Input Current	39 [A]
Rated Number of Rotations	2000 [r.p.m.]
Under-voltage Protection	42 [V]
Over-voltage Protection	54 [V]

Fig.4 shows BLDC motor and motor driver in the bogie and its constitution.

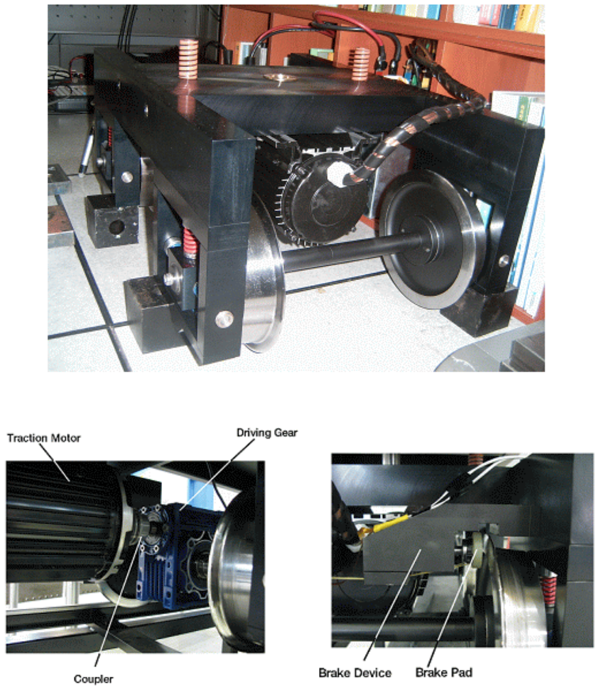


Fig.4 Structure of the driving bogie

2.3 Active Steering Controller

The dSPACE system (DS1103 PPC Controller Board) is a powerful controller board for rapid control prototyping [36]. This board is mounted in a dSPACE expansion box to test the active steering control functions in a scaled railway vehicle.

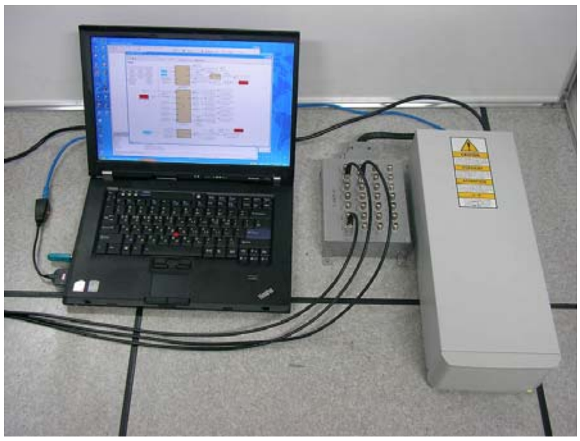


Fig.5 Active steering controller module: MATLAB/ SIMULINK and dSPACE

Table 3 Specification of the DS1103 PPC Controller Board

Processor	Type	PPC 750GX
	CPU Clock	1GHzCache
	Cache	32KB level 1 instruction and data cache, 1MB level 2
	Bus frequency	133MHz Memory
Memory	Local	32MB SDRAM
	Global	96MB SDRAM
ADC	Channels	16 multiplexed channels, 4 parallel channels
	Resolution	16-bitOutput range
	Input range	±10 [V]
	Over-voltage Protection	±15 [V]
DAC	Channels	8 channels
	Resolution	16-bit Output range
	Output range	±10 [V]
Digital I/O	Channels	32bit Parallel I/O
	Voltage Range	TTL I/O Level

The research vehicle has an active steering controller that works in coordination with control signals of the steering controller to alleviate wheel/rail contact forces and to decrease wheel/rail wear.

3 Fuzzy Controller Design for Active Steering Bogie System

3.1 Modeling of Fuzzy System

The idea of fuzzy sets was introduced by Zadeh in 1965[1]. Currently one of the more active areas of fuzzy logic applications is control system. Fuzzy control systems are rule-based systems, which have a set of fuzzy IF-THEN rules represents a control decision mechanism to tracking the reference line. We take min-max fuzzy reasoning method for 49 rules and utilize the centroid defuzzification method [2]~[4].

$$e(k) = r(k) - y(k) \qquad (1)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (2)$$

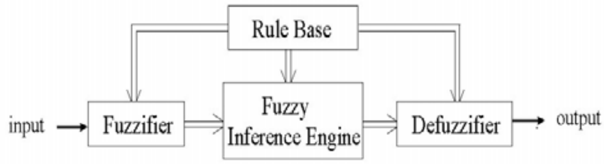


Fig.6 Schematic views of an active steering bogie

The complete set of model rules can be contained in a look up rule base such as in Fig.7. This rule base represents a highly nonlinear dynamical system. Typically, fuzzy logic controllers operate on minimizing an error function such as tracking or command error. The antecedent elements in the controller rules are the linguistic variables. Error and change of error, and the rule consequent is $u = f(e, \Delta e)$, through rules of the form:

$$IF \;\; e \text{ is } A_i \text{ AND } \Delta e \text{ is } B_i \text{ THEN } u \text{ is } C_i \qquad (3)$$

where (A,B,C) are linguistic terms such as the 7 sets NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZE(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big), see Fig. 7.

		Δe						
		NB	NM	NS	ZE	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NM	NM	NS	ZE	PS
	NS	NB	NM	NS	NS	ZE	PS	PM
e	ZE	NM	NM	NS	ZE	PS	PM	PM
	PS	NM	NS	ZE	PS	PS	PM	PB
	PM	NS	ZE	PS	PM	PM	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

Fig.7 MacVicar-Whelan fuzzy rules for the servo control [4]

The PD-type fuzzy logic controller for active steering as illustrated in Fig.8. The normalized and denormalized gain values is K_e =0.7, $K_{\Delta e}$ =2.4 and K_u =2.05 for lead-ing axle controller, and K_e =0.5, $K_{\Delta e}$ =2.05 and K_u =1.25 for trailing axle controller.

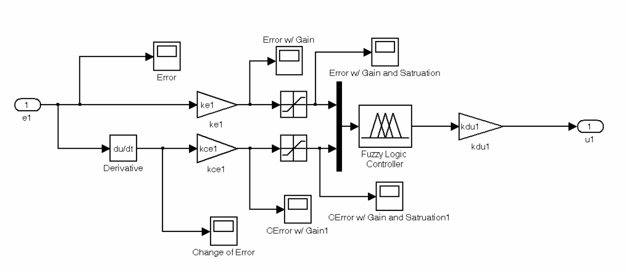


Fig.8 PD-type fuzzy logic controller in MATLAB/SIMULINK

3.2 Degree of non-uniformity of triangular fuzzy membership functions

We propose a technique for improving the performance of fuzzy control systems by adaptively changing the widths of triangular fuzzy membership functions according to characteristic of the transient response. The degree of non-uniformity defines non-uniform width of triangular membership functions. A method of determining the input and output gain parameters for satisfying desired performance requirement was also considered. Assigning bigger value of the degree of non-uniformity to the decreasing- error interval and smaller value to the increasing-error interval improves significantly the performance of the fuzzy control systems.

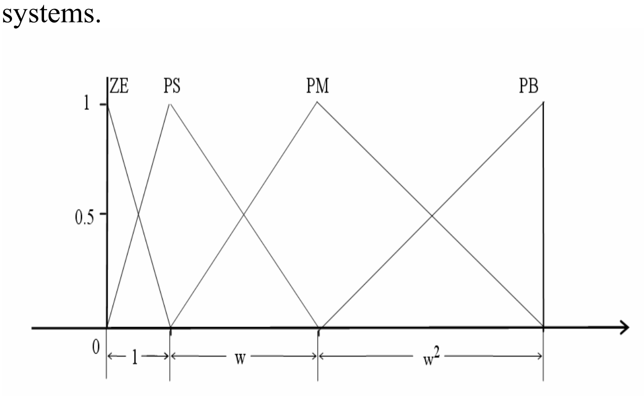
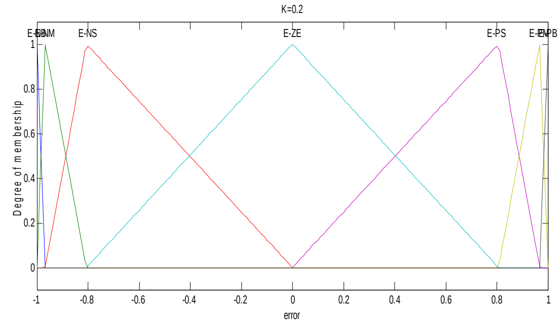
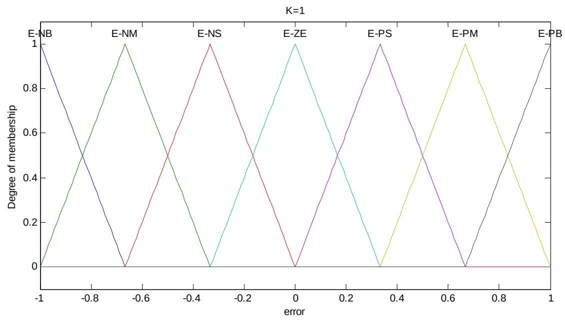


Fig.9 Definition of nonuniformity by changing the widths of triangular fuzzy membership functions

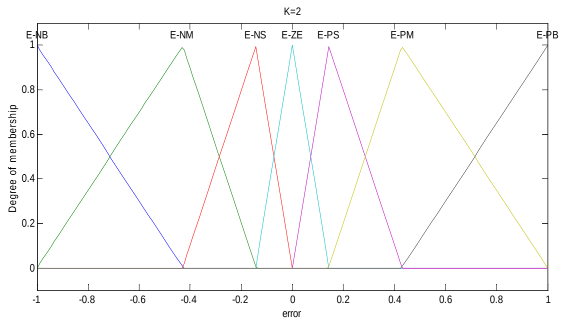
Fig.10 shows a kind of membership function shape for e(k), Δe(k), and u(k) at various values of non-uniformity *k* of fuzzy membership function.



(a) k=0.2

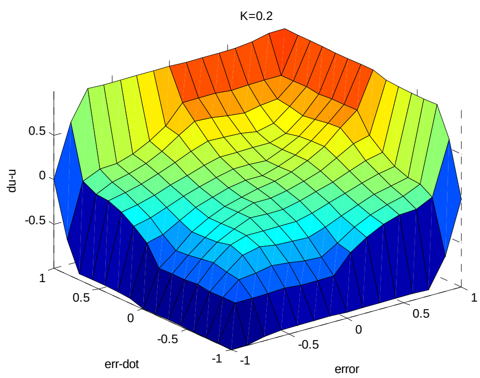


(b) k=1.0

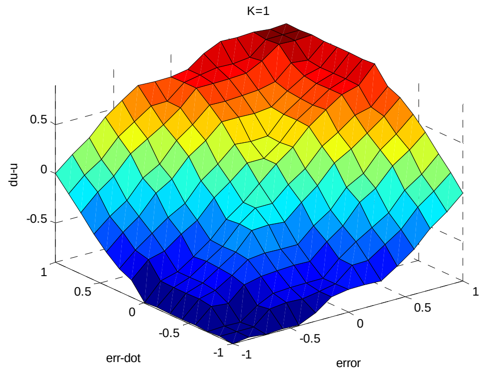


(c) k=2.0

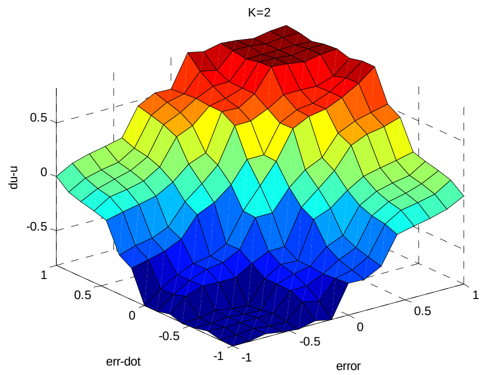
Fig.10 Membership function for e(k), Δe(k), and u(k) at various values of the degree of the non-uniformity (that is *k*) of fuzzy membership function



(a) k=0.2



(b) k=1.0



(c) k=2.0

Fig.11 Rule surface at various values of non-uniformity k of fuzzy membership function

Fig.11 represents the fuzzy rule surface at various values of non-uniformity k of fuzzy membership function.

4 Experiments of Test-bed

4.1 Experiment Environment

Fig.12 1/5 Scale railway vehicle and curved track for research

Two axle bogies are used for the 1/5 scaled railway vehicle. Experimental equipment with a scale model of 1/5 is designed and used for the performance analysis of the active steering control system. The dSPACE system (DS1103 PPC Controller Board) is used for implementing the active steering controller.

The R=20 and 27.11 [m] length curved track is used in this experiment as shown in Fig.12. The research vehicle runs at a speed of 2[m/s], which the vehicle speed is calculated by the number of wheel rotation that is measured with a photoelectric sensor.

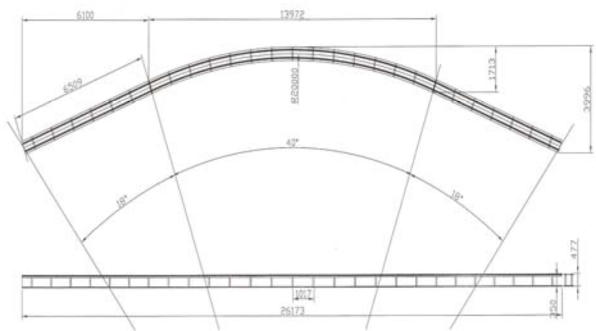


Fig.13 Schematic views of 1/5 scaled curve track for running test of the scaled active steering vehicle

To detect the wheel/rail relative displacement, we utilize four laser sensors which are installed both end of front and rear axles. Its values are directly measured from the laser sensors by means of converting voltage values into millimeter values. The center line of front and rear axles can be obtained as equation (4).

$$y_{front} = \frac{y_2 - y_1}{2}, \; y_{rear} = \frac{y_4 - y_3}{2} \tag{4}$$

where y_1 and y_2 mean laser sensor signals which is installed both ends of the front axle, y_3 and y_4 represent laser sensor signals which is installed both ends of the rear axle, and y_{front} and y_{rear} denote center lines of the front and rear axle.

The reference lateral displacement is calculated as equation (5).

$$y_d = \frac{r_0 l}{R\lambda} \quad (5)$$

where l denotes a half gauge of wheelsets (=0.15 [m]), r_0 represents a wheel radius (=0.086 [m]), and λ means a heel conicity (=0.2).

The actuator force of active steering bogie is proportional to the input voltage values as equation (6). That is, the actuator force increases from 0 [N] to 200 [N] approximately proportionally to the actuator command voltage (0 [V] to 4 [V]).

$$F_{act} = 50V_{con} \quad (6)$$

where F_{act} means a actuator force[N] and V_{con} represents a voltage command [V].

4.2 Experimental Results

The proposed fuzzy controller with the degree of non-uniformity has been tested and compared with a conventional fuzzy controller. Outputs from the scaled active steering testbed during an running experimental test on the curved track were used to implement the degree of non-uniformity. We try to design fuzzy control system having optimized parameters which is defined as a degree of non-uniformity of triangular fuzzy membership functions.

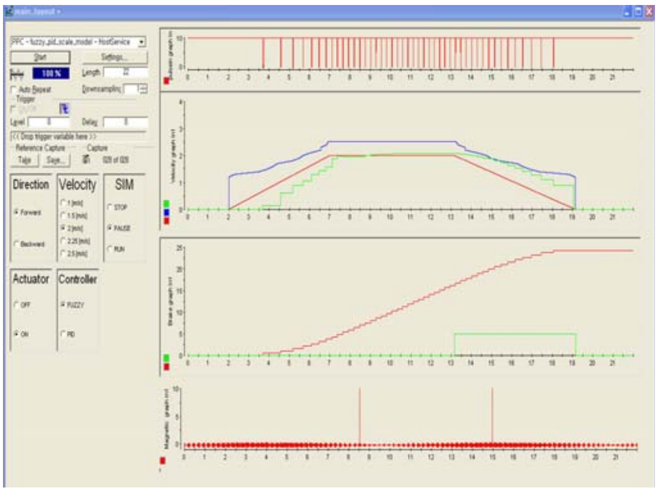


Fig.14 The experimental results: the pulse train for calculating the vehicle speed, the vehicle speed and the reference speed command, the moving distance, and the magnetic sensor signals for curve detection, respectively.

Pulse train for calculating the vehicle speed, (b) velocity profile for driving bogie (red-line: the vehicle velocity profile [m/s], blue-line: the real voltage [v], green-line: the vehicle speed [m/s])

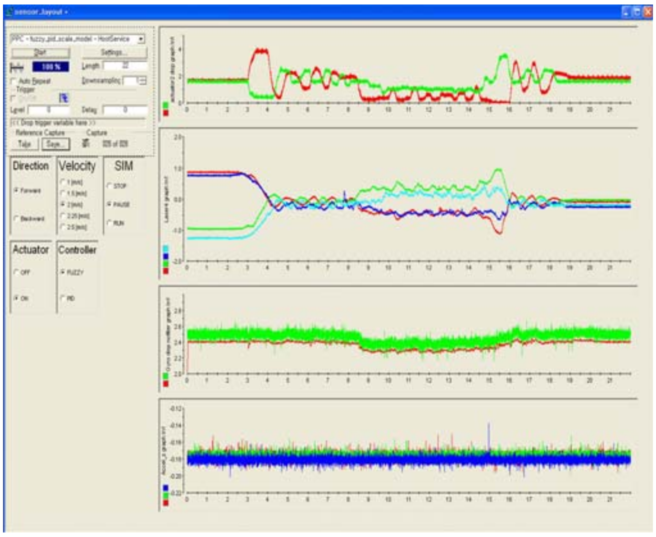
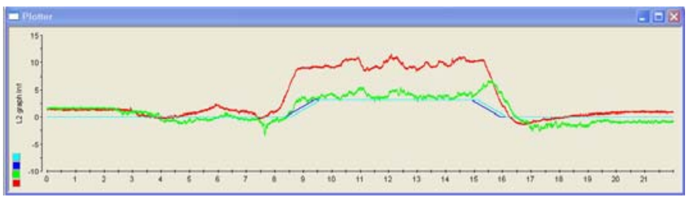


Fig.15 The experimental results (various sensor outputs): the actuator displacement signals, the four laser sensor output signals for relative displacements, the gyro sensor signals for measuring the bogie yaw angle, and the accelerometer output for a characteristic vibration of car-body, respectively.

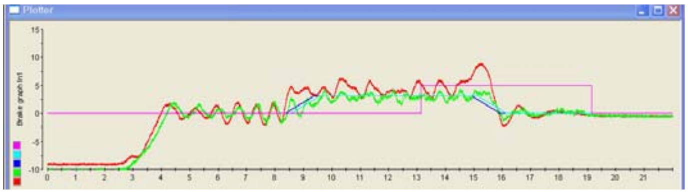
Fig. 15 show various sensor outputs which are measured with a magnetic sensor for detection of the start/end point of the curve track and accelerometer for a characteristic vibration of car-body.

Here is a Fig.16 which shows the result of the relative lateral displacement in case of no steering and fuzzy active steering control at various values of non-uniformity *k*. The reference displacement of the front and rear axle is 3.085 [mm] as the equation (5).

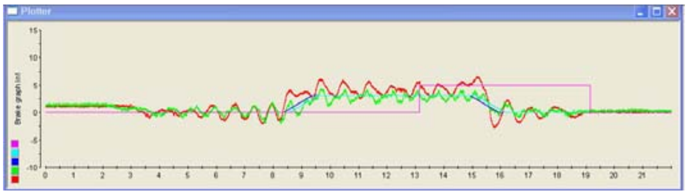


(a) Passive system (no control)

(b) Fuzzy control system with k=0.2



(c) Fuzzy control system with k=1.0



(d) Fuzzy control system with k=2.5

Fig.16 Experimental results: relative displacement between wheel and rail (red-line: the front axle center line of the wheel/rail relative displacement [mm], green-line: the rear axle center line of the wheel/rail relative displacement [mm], blue-line: reference displacement of the front axle [mm], cyan-line: reference displacement of the rear axle [mm])

5 Conclusion

In this paper, we present active steering controller design in the railway systems using fuzzy controller design method. Control strategy to the active steering system based on two axle vehicle attached to actuator of the yaw torque considering the riding quality has been applied. The dSPACE system is used for implementing the active steering controller. The proposed fuzzy controller with the degree of non-uniformity membership functions for active steering is tested in the 1/5 scale research vehicle and R=20 curved track, and we could verify the effectiveness and performance of the proposed system. Experiment results show that the proposed fuzzy controller robustly yields good performance comparing with the passive system and the conventional controller.

References:

[1] Zadeh, L. A. Fuzzy Sets, *Information and Control*, Vol. 8(3), 338-353, 1965.

[2] Mamdani, E. H. and Assilian, S., An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller, *International Journal of Man Machine Studies*, Vol. 7 (1), 1-13, 1975.

[3] Sugeno, M., *Industrial Applications of Fuzzy Control*, Elsevier Science Pub., 1985.

[4] MacVicar-Whelan P. J., Fuzzy Sets for Man-Machine Interaction, *Int. J. Man-Machine Studies*, Vol.8, 687-697, 1976.

[5] Simon Iwnicki, *Handbook of Railway Vehicle Dynamics (Eds)*, Taylor&Francis, 2006.

[6] V. K. Garg, R. V. Dukkipati, *Dynamics of Railway Vehicle Systems*, Academic Press, 1984

[7] A. Matsumoto, Y. Sato, Multibody Dynamics Simulation and Experimental Evaluation for Active-Bogie-Steering Bogie, *Int. Symposium on Speed-Up and Service Technology for Railway and Maglev Systems*, 2006

[8] J. Pèrez, R. M. Goodall, Control Strategies for Active Steering of Bogie-based Railway Vehicles, *Control Engineering Practice*, 2002.

[9] J. T. Pearson, R. M. Goodall, An Active Stability System for a High Speed Railway Vehicle, *Electronic Systems and Control Division Research*, 2003

[10] Katsuya Tanifuji, Active Steering of a Rail Vehicle with Two-Axle Bogies based on Wheelset Motion, *Vehicle System Dynamics*, 2003.

[11] M. Athans, The Role and Use of the Stochastic Linear-Quadratic-Gaussian Problem in Control System Design, *IEEE Trans. on AC*, 16(3), 1971

[12] T.X. Mei, T.M. Goodall, Recent Development in Active Steering of Railway Vehicles, *Vehicle System Dynamics*, 2003.

[13] Yoshihiro Suda, Takefumi Miyamoto, Active Controlled Rail Vehicles for Improved Curving Performance and Response to Track Irregularity, *Vehicle System Dynamics Supplement*, 2001.

[14] S.Y. Lee and Y. C. Cheng, Nonlinear Analysis Hunting Stability for High-Speed Railway Vehicle Trucks on Curved Tracks, *Vehicle System Dynamics Supplement*, Vol.127, 2005

[15] S. Shen, T. X. Mei, Active Steering of Railway Vehicles: A Feedforward Strategy, *European Control Conference*, 2003

[16] A. D. Monk-Steel, An Investigation into the Influence of Longitudinal Creepage on Railway

Squeal Noise due to Lateral Creepage, *Journal of Sound and Vibration*, 2006

[17] H. Scheffel, R. D. Frohling, and P. S. Heyns, Curving and Stability Analysis of Self-Steering Bogies Having A Variable Yaw Constraint, *Vehicle System Dynamics Proc. of 13th IAVSD Symp. on the Dynamics of vehicles on Roads and on Tracks*, Vol. 23(Suppl.), 1993, pp. 425-436

[18] A. H. Wickens, Static and Dynamic Stability o f Unsymmetric Two-Axle Railway Vehicles Possessing perfect Steering, *Vehicle System Dynamics*, Vol. 11, 1982, pp. 89-106

[19] A. H. Wickens, Railway Vehicles with Generic Bogie Capable of Perfect Steering. *Vehicle System Dynamics*, Vol. 25, 1996, pp. 389-412

[20] Y. Suda, T. Fujioka, and M. Iguchi, Dynamic Stability and Curving Performance of Railway Vehicles, *130Bull. JSME*, 29(256), 1986, pp. 3538-3544

[21] C. E. Bell, and D. Horak, Forced Steering of Rail Vehicles: Stability and Curving Mechanics, *Vehicle System Dynamics*, Vol. 10, 1981, pp. 357-386

[22] Y. Suda, High Speed Stability and Curving Performance of Longitudinally Unsymmetric Trucks With Semi-Active Control, *Vehicle System Dynamics*, Vol. 23, 1994, pp. 29-51

[23] T. Fujioka, Y. Suda, and M. Iguchi, Representation of Railway Suspensions of Rail vehicles and Performance of Radical Trucks, *Bull. JSME 27*, 1984, pp.2249-2257

[24] S. Narayana, R. V. Dukkipati, and M. O. M. Osman, A Comparative Study on Lateral Stability and Steady State Curving Behavior of Unconventional Rail Truck Models, *Proc. Inst. Mech. Eng., F J. Rail Rapid ransit 208*, 1994, pp. 1-13

[25] S. S. Marayana, R. V. Dukkipati, and M. O. M. Osman, Analysis of modified Railway Passenger Truck Designs to Improve Lateral Stability/Curving Behavior Compatibility, *Proc. Inst. Mech. Eng., F J. Rail Rapid Transit 209*, 1995, pp.49-59

[26] S. S. Marayana and R. V. Dukkipati, Lateral Stability and Steady State Curving Behavior Performance of Unconventional Rail Trucks, *Mech. Mach. Theory 36*, 2001, pp. 577-587

[27] R. V. Dukkipati, and S. S. Marayana, Non-Linear Steady-State Curving Analysis of Some Unconventional Rail Trucks, *Mech. Mach. Theory, 2001*, pp. 507-521

[28] R. V. Dukkipati, and S. S. Marayana, and M. O. M. Osman, Curing Analysis of Modified Designs of Passenger Railway Vehicle Trucks, *JSME int. J., Ser.* C 25(1), 2002, pp. 159-167

[29] G. Lorant, and G. Stepan, The Role of Nonlinearities in the Dynamics of a single Railway Wheelset, *Machine Vibration 5*, 1996, pp. 18-26

[30] T. Matsudaira, Shimmy of Axle with Pair of Wheels, *Journal of Railway Engineering Research*, 1952, pp. 16-26

[31] T. Matsudaira, N. N. Matsui, W, Arai, and K. Yokos, Problems on Hunting of Railway Vehicle on Test Stand. Trans, *A.S.M.E Journal of Engineering In industry*, Vol. 91, Ser. B, no. 3 , 1969, pp. 879-885

[32] L. M. Sweet, J. A. Sivak, and W. F. Putman, Non-linear Wheelset Forces in Flange Contact, Part I: Steady State Analysis and Numerical Results, Part 2: Measurement using Dynamically Scaled Models, *Journal of Dynamic Systems, measurement and Control*, Vol. 101, 1979, pp. 238-255

[33] L. M. Sweet, A. Karmel, and S.R. Fairley, Derailment Mechanics and safety Criteria for Complete Railway Vehicle Trucks, In: Wickens, A. (ed.): *The Dynamics of Vehicles on Roads and Trac*ks. PROC. 7TH IAVSD Symposium, Cambridge, UK, 1981

[34] A. Jaschinski, *On the Application of Similarity Laws to a Scaled Railway Bogie Model*, Dissertation, TU-Delft, 1990

[35] M. Gretzschel and A. Jaschinski, Design of an Active Wheelset on a Scaled Roller Rig, *Vehicle System Dynamics*, Vol. 41 No.5, 2004, pp. 365-381

[36] dSPACE, *Solution for Control*, 2007.

[37] M. S. Kim, Y. S. Byun, Y. H. Lee and K. S. Lee, Gain Scheduling Control of Levitation System in Electromagnetic Suspension Vehicle, *WSEAS Transactions on Circuits and Systems*, Vol.5, pp.1706-1712, 2006.

[38] M. S. Kim, Y. S. Byun, Y. H. Lee and K. S. Lee, The Levitation Controller Design of an Electromagnetic Suspension Vehicle using Gain Scheduled Control, *5th WSEAS Int. Conf. on Circuits Systems, Electrics, Control & Signal Processing*, 2006.

[39] M. S. Kim, Y. S. Byun and H. M. Hur, Design of the Active Steering Controller of Scaled Railway Vehicle Improving Curving Performance, *The 7th WSEAS Int. Conf. on Circuits Systems, Electrics, Control & Signal Processing*, 2008

[40] M. S. Kim, J. H. Park, and W. H. You, Construction of Active Steering Control System for the Curving Performance Analysis of the Scaled Railway Vehicle, *The 7th WSEAS Int. Conf. on Circuits Systems, Electrics, Control & Signal Processing*, 2008

[41] Min-Soo Kim, Yeun-Sub Byun, Hyun-Moo Hur, Design of Active Steering Controller of the Scaled Railway Vehicle, *INTERNATIONAL JOURNAL OF CIRCUITS, SYSTEMS and SIGNAL PROCESSING*, Vol.2 No.3, 2008.

[42] Min-Soo Kim, Joon-Hyuk Park, Won-Hee You, Construction of Active Steering System of the Scaled Railway Vehicle, *INTERNATIONAL JOURNAL OF SYSTEMS APPLICATIONS, ENGINEERING & DEVELOPMENT*, Vol.2, No.4, 2008.

[43] Min-Soo Kim, Design of the Active Steering Fuzzy Controller with the Degree of Non-uniformity for a Scaled Railway Vehicle, *The 9th WSEAS International Conference on ROBOTICS, CONTROL and MANUFACTURING TECHNOLOGY (ROCOM '09)*, Hangzhou, China, May 20-22, 2009.