Construction of Active Steering System of the Scaled Railway Vehicle

Min-Soo Kim, Joon-Hyuk Park and Won-Hee You

Abstract**—** Active steering system of railway vehicles is designed to alleviate wheel/rail contact forces and to decrease wheel/rail wear. This paper describes the construction of active steering control system for the curving performance analysis of scaled railway vehicle. The active steering control system consists of the remote control station module, the steering controller module, the battery module, the driving bogie module, the steering bogie module, and various sensors module. Generally scaled railway vehicles were developed to reproduce the fundamental dynamic behavior of the full size railway vehicle in laboratory conditions. The proposed active steering control system 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.

Keywords**—** Active Steering, Control System, Railway Vehicle, Scaled Model.

I. INTRODUCTION

BY characteristics of the wheel conicity and rigid connection of two wheelsets by an axle, railway vehicles naturally have self-steering ability running on curved tracks. In curving negotiation, wheel/rail interaction forces is vital in the design of suspension system and steering system that lead to the variation in lateral forces between wheels and rails. These lateral forces are mainly responsible of wear on wheels and rails. But this mechanism inherently has two problems. One is a hunting phenomenon by a self-excited vibration of the wheelsets and the other is the limitation of the curving ability by only self-steering mechanism [1][2]. For many years plentiful of research has been tried to solve the difficult design trade-off between the stability and curving performance. 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 [3]-[12].

To alleviate 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 [3]-[25].

In this paper, we design an experimental testbed with a vehicle and a track of 1/5 scale model and perform the curving performance verification of the proposed active steering control system.

Generally scaled railway vehicles were developed to reproduce the fundamental dynamic behavior of the full size railway vehicle in laboratory conditions. In this paper, 1/5 scaled railway vehicle is carried out for the development and testing of prototype bogie, and the investigation of fundamental railway vehicle running behavior [26]-[31].

This paper is organized as the followings. Section II describes an active steering control system for 1/5 scale model. Section III explains the construction of test-bed and section IV contains the experiment results. The main conclusions are then summarized in section V.

II. ACTIVE STEERING CONTROL SYSTEMS

When a railway vehicle negotiates a curve, significant lateral forces develop between wheels and rails. The dynamic interaction forces of the vehicle and the bogie develop owing to the kinematics of profiled wheels and the imbalance between gravitational and centrifugal force.

The basic concept of steering control strategy is to apply a controlled torque to the wheelset in the yaw direction. This can be achieved through longitudinal actuators as shown in Fig.1. This strategy is founded on the coupling of the lateral and yawing motions of the wheelsets by using the laser sensor signals represented in the wheel/rail displacement.

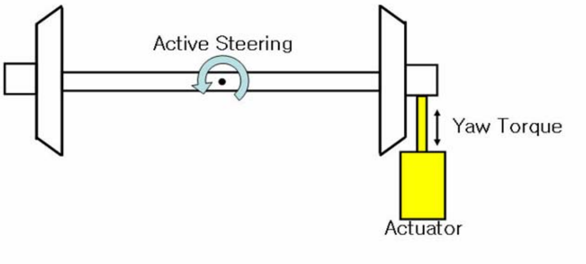

Fig.1 Active steering control strategy: apply a controlled torque to the wheelset in the yaw direction

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Manuscript received December 31, 2008: Revised version received March 4, 2008.

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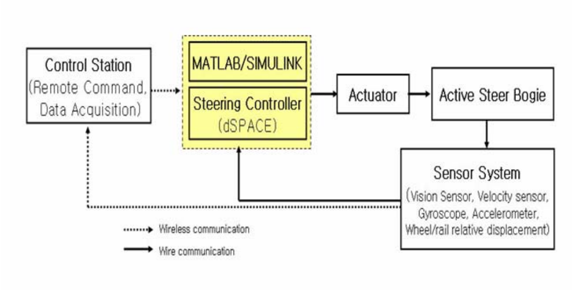


Fig.2 Block diagram of active steering control system

Fig.2 shows a block diagram of the active steering control system using MATLAB/SIMULINK for the research vehicle.

An F-link type steering bogies which consists of two steering actuators and several links is depicted in Fig.3.

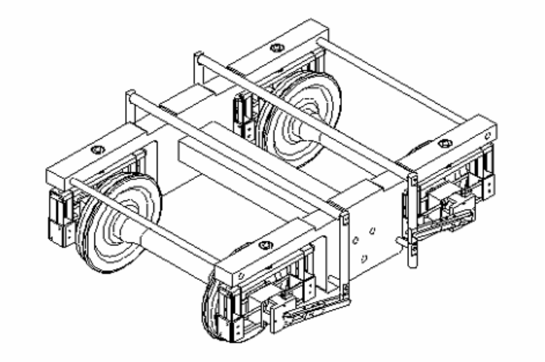


Fig.3 Schematic views of an active steering bogie

Table I Composition of the testbed for the active steering control

Module	Accomplishment Contents
Control Station Module	▪Remotely speed and the direction command transmission ▪ Steering controller signal monitoring ▪Wheel/rail contact image acquisition using wireless camera systems
Steering Controller Module	▪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 Module	▪Creation of yaw moment corresponding to the control signals ▪Actuator displacement output
Sensor System Module	▪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

The relative movement between the wheels and the rail measured by laser sensors is considered as the system output. These laser sensors are installed at the both ends of the wheelset for sensing the distance of the laser sensor from axle box to rail head.

The lateral displacements of front and rear axles are directly measured from four laser sensors. The center line of front and rear axles can be obtained as (1).

$$y_{front} = \frac{y_2 - y_1}{2}, \quad y_{rear} = \frac{y_4 - y_3}{2} \tag{1}$$

where y_i means laser sensor signals output which is installed both ends of the front axle, and y_{front} and y_{rear} denote center lines of the front and rear axle.

And these measured values are compared with the reference input which is calculated as (2).

$$y_d = \frac{r_0 l}{R\lambda} \tag{2}$$

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

III. CONSTRUCTION OF TESTBED

Testbed is carried out for the development and testing of active steering bogie. The testbed mainly consists of seven components:

- Curved track module
- Control station module
- Driving bogie module
- Steering bogie module
- Steering controller module
- Battery module
- Sensors system module

A block diagram of testbed for the active steering control system is given in Fig.4.

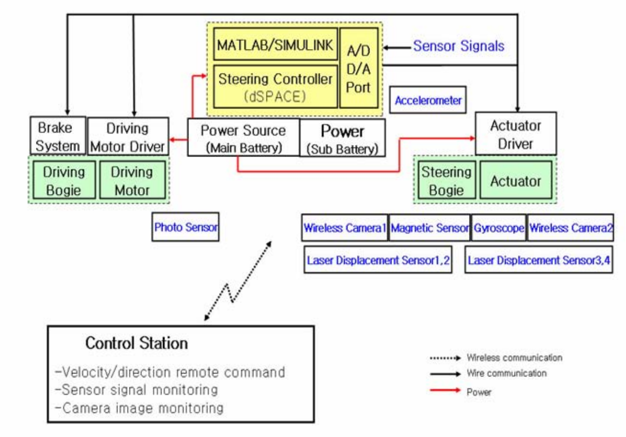


Fig.4 Block diagram of active steering control system

A. *Curved Track Module*

For running test, 27.11 [m] and R=20 curved track is used. This track has not a cant, and consists of the straight track (6.41m), curve track (14.30m) and straight line track (6.41m).

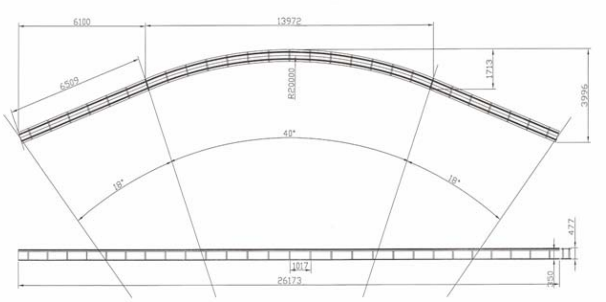


Fig.5 Drawings of the curved track of testbed for running test for active steering control system

Fig.6 Research testbed: the 1/5 scale active steering vehicle and the curved track

B. *Control Station Module*

The control station module takes functions as remote control of the research vehicle, remotely signal monitoring of the steering controller, and the image data acquisition of wheel/rail contact using wireless camera systems. Control station module for remote control and signal monitoring remotely as shown in Fig.7.

Fig.7 Control station module for remote control and signal monitoring remotely

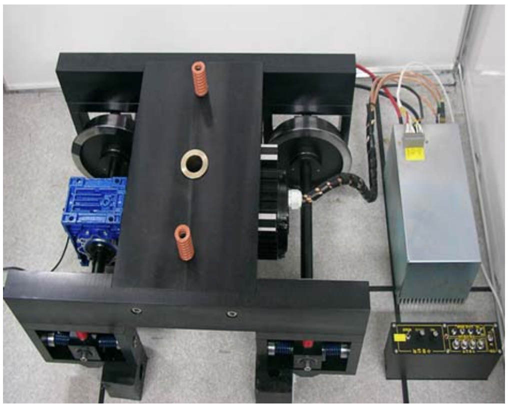
C. *Driving Bogie Module*

Driving bogie module consists of a BLDC motor of DC 48[V] 39.1[A], a 5:1 reduction gear, 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.

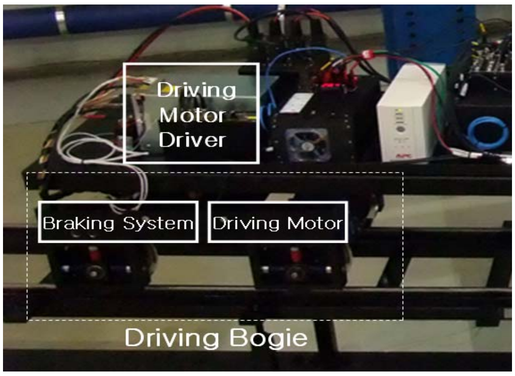
Table II Specification of the BLDC motor

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

Fig.8 shows BLDC motor and motor driver in the bogie and its constitution.



(a) BLDC motor and motor driver in the bogie



(b) Constitution of the driving bogie

Fig.8 Driving bogie module

D. *Active Steering Controller Module*

The dSPACE system (DS1103 PPC Controller Board) is a powerful controller board for rapid control prototyping [32]. This board is mounted in a dSPACE expansion box to test the active steering control functions in a scaled railway vehicle.

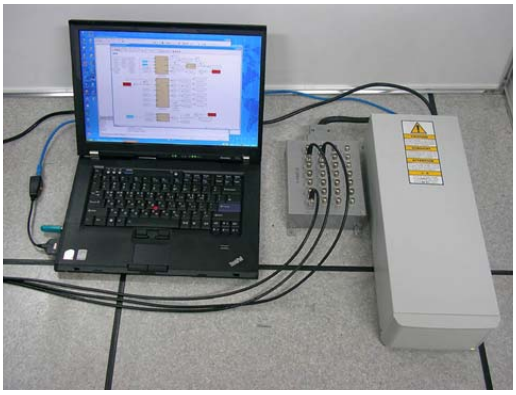


Fig.9 Active steering controller module: MATLAB/ SIMULINK and dSPACE

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. The role of the active steering control module is followings:

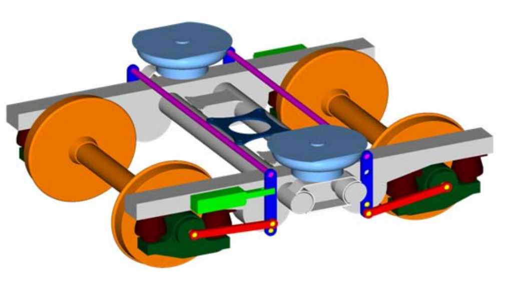
- Generation of steering command to actuator based on the control algorithm
- A/D and D/A input/output terminals
- MATLAB/SIMULINK and dSPACE as a rapid control prototyper

Table III Specification of the DS1103 PPC Controller Board

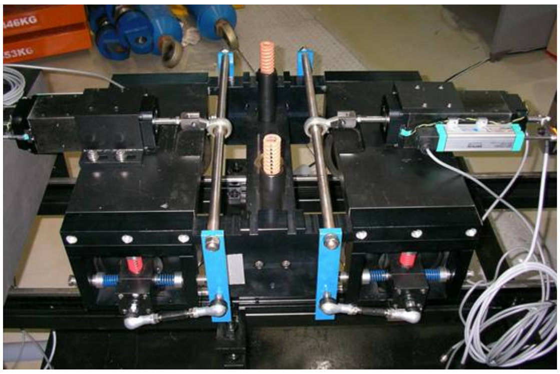
Processor	Type	PPC 750GX
	Clock	1GHzCache
	Bus frequency	133MHz Memory
Memory	Local	32MB SDRAM
	Global	96MB SDRAM
ADC	Channels	16 multiplexed channels, 4 parallel channels
	Resolution	16-bitOutput range
	Input range	±10 [V]
	Over-voltage Protection	±15 [V]
DAC	Channels	8 channels
	Resolution	16-bit Output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

E. *Steering Bogie Module*

The steering bogie of F-link type which consists of two steering actuators and several links is depicted in Fig.10.



(b) Schematic view of steering bogie



(b) Actual driving bogie: F-link type

Fig.10 Active steering bogie module

The actuator force is proportional to the input voltage values. That is, the actuator force increases from 0 [N] to 200 [N] approximately proportionally to the actuator command voltage (0 [V] to 4 [V]).

$$F_{act} = 50 V_{com} \tag{3}$$

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

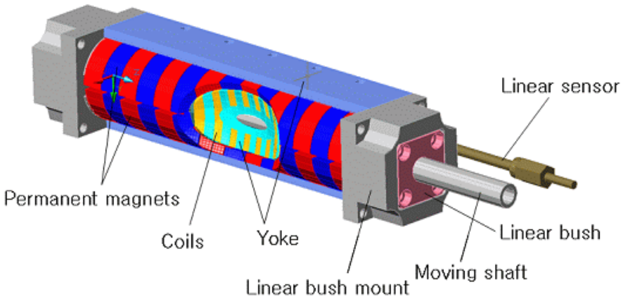


Fig.11 Schematic view of linear tabular motor of F-link type

F. Battery Module

Battery module is composed of the main battery part for providing a driving motor, two actuators and a controller with power, and the auxiliary battery part for supplying power to several sensors.

The main battery part consists of one 48[V] 40[Ah] lithium-ion-polymer battery pack and two 24[V] 20[Ah] lithium-ion-polymer battery packs, while three 13.2[V] 2300[mAh] LiFePO4 battery packs make up the auxiliary battery part.

(a) The main battery part for providing a driving motor, two actuators and a controller with power

(b) The auxiliary battery part for supplying power to several sensors

Fig.12 Battery module

G. Sensor System Module

For active steering control of the testbed, it is vital to know the exact relative displacement of wheel/rail, vehicle speed, radius of the curve track, and so on. The sensor system of the testbed mainly consists of four components:

- Wheel/rail relative displacement measurement using laser sensor
- Carbody vibration characteristic measurement using accelerometer sensor
- Yaw angle measurement of the steering bogie using gyro sensor
- Detection of the start/end point of the curve track using magnetic sensor
- Wheel/rail dynamics monitoring using wireless camera systems

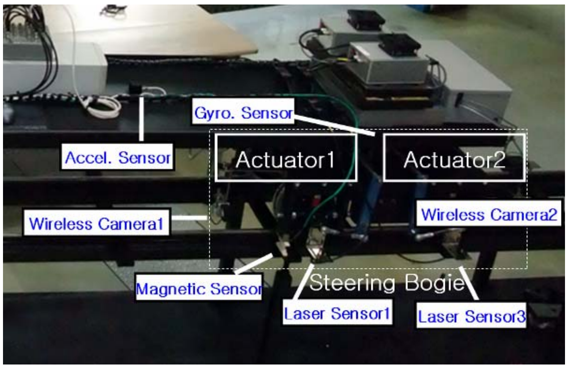
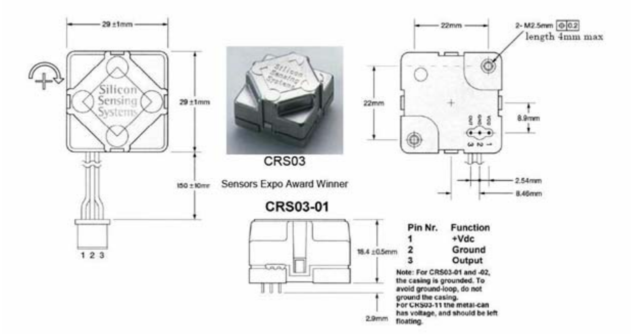


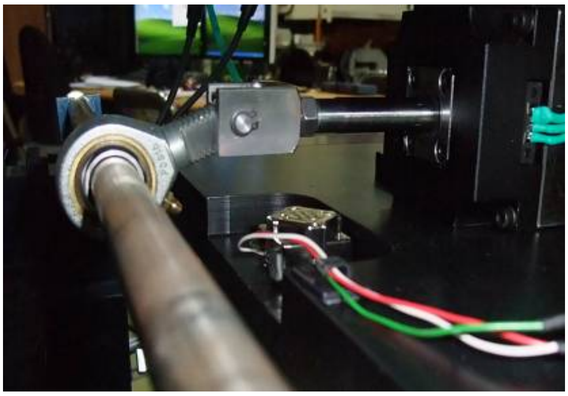
Fig.13 Sensor system module of the testbed

Table IV Specification of the laser sensor

Method of Detection	Diffuse Reflective
Sensing Distance	10 ±4 [cm]
Supply Voltage	DC 10~ 30 [V]
Weight	60 [g]
Dimensions	10×10 [cm]



(a) Gyroscope sensor (Silicon Sensing CRS03-02)



(b) Gyroscope sensor mounted on the pivot center

Fig.14 Gyroscope sensor for measurement of yaw angle and curve radius

Table V Specification of the gyroscope sensor

Rate Range	0 ~ ±100 [degree]
Supply Voltage	DC 5 [V]
Scale Factor	20
Output Voltage	2.5 ±2.5 [V]
Under-voltage Protection	42 [V]
Dimensions	29×29×18.4 [mm]

Magnetic sensor for detecting the start/end point of the curve track is shown in Fig.15.

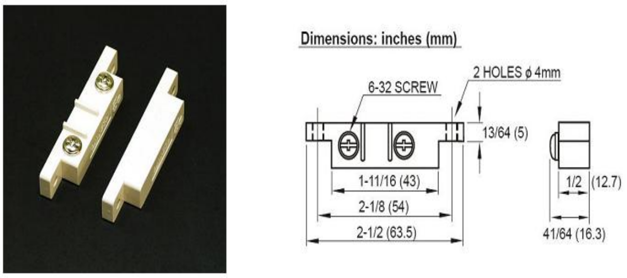


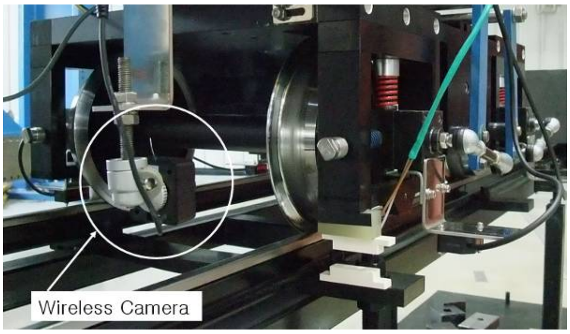
Fig.15 Magnetic sensor for detection of the start/end point of the curve track

Table VI Specification of the magnetic sensor

Contact Type	Normal open
Contact Rating	10VA
Breakdown	DC 220 [V]
Magnet Type	Anisotropic Ferrite
Operating Gap	3/4″

The experimental facility for examination on the lateral wheel/rail displacement of the active steering controller is made of the 2.4 [GHz] wireless cameras as shown in Fig.16.

(a) Wireless camera and receiver



(b) Position of the wireless camera

(c) Wheel/rail contact monitoring at the control station

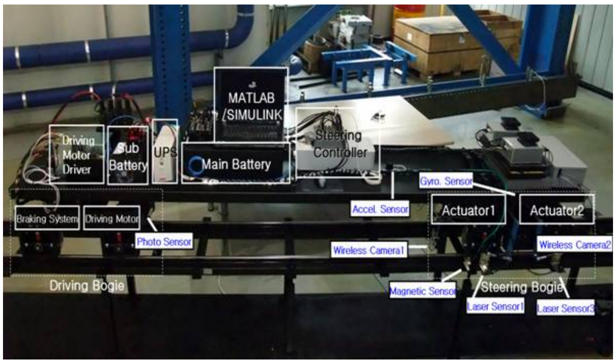
Fig.16 Wheel/rail dynamics monitoring system using wireless camera systems

IV. EXPERIMENTS OF TESTBED

In the running test of the research vehicle, the testbed for the active steering control system can be tried and validated under real-time condition.

Fig. 17 shows the testbed for the active steering control system. The measuring signals of the relative displacement of wheel/rail are transmitted to the dSPACE controller via A/D converter, these signals are process based on the control algorithm, and finally the signals are retransmitted to the steering actuator through D/A converter. The steering bogie of the vehicle model was driven by the driving bogie at 2 [m/s] speeds. For running test, 27.11 [m] and R=20 curved track is used.

(a) The 1/5 scaled test vehicle



(b) Modular structure

Fig.17 The 1/5 scaled testbed for the active steering control system

A. Test Results of the Driving Bogie Module

Load test is performed with scale roller rig in order to analyze the velocity characteristic of a BLDC driving motor according to variation of the input voltage condition.

Fig. 18 shows the scaled roller rig for the load test of the driving motor and Fig. 19 displays the load test results of the driving motor.

The vehicle speed can be adjusted from 0 [m/s] to 3.8 [m/s] by changing of the input voltage between 0 [V] and 4 [V] at the control unit of the diving motor in the driving bogie. Fig.9 shows the load test results of the driving motor as velocity - voltage curve.

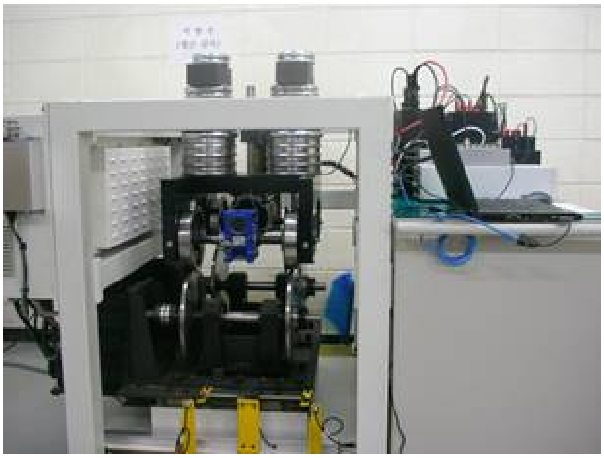
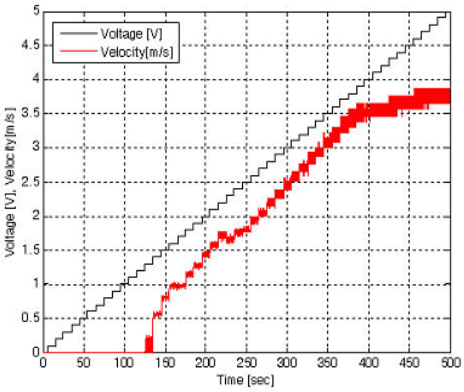
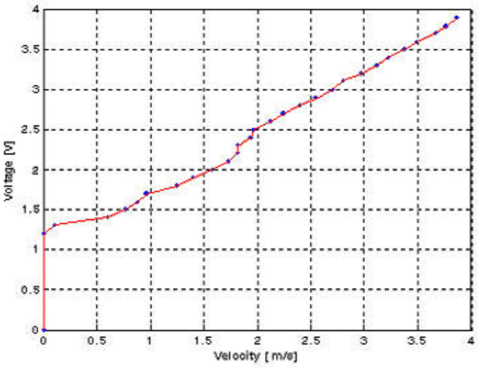


Fig.18 Scaled roller rig for the load test of the driving motor



(a) Velocity curve according to variation of the input voltage



(b) Velocity - voltage curve

Fig.19 Load test results of the driving motor

B. Test Results of the Steering Bogie Module

For analyzing the steering actuator which is made of a linear tabular motor, we perform the frequency response analysis. As a result of test, we examine that its bandwidth is measured as 3 [Hz]. Fig.20 indicates the linear tabular motor as a actuator for steering bogie.

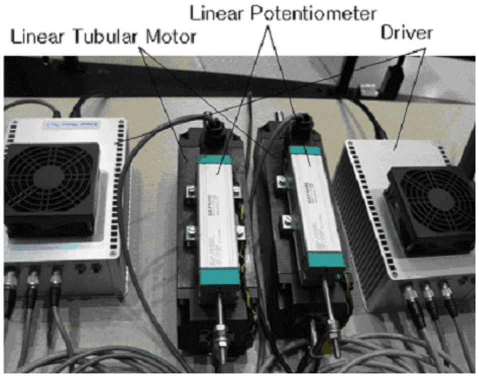
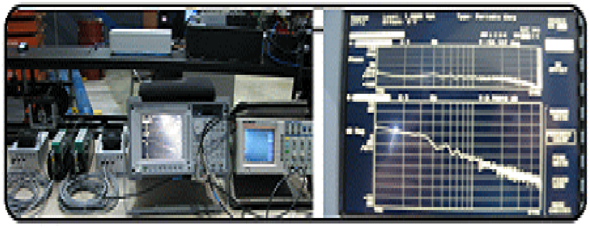
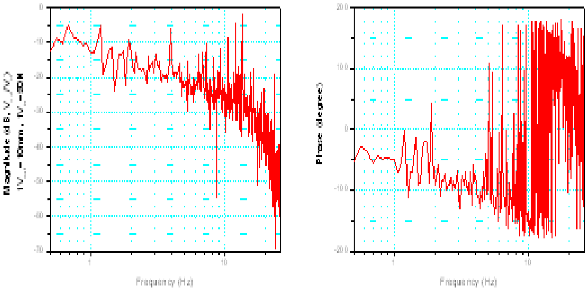


Fig.20 Linear tabular motor for actuator

Fig.21 shows the test bench and its results for calculating the frequency response, and results of the frequency response analysis of the steering bogie



(b) Test bench for calculating the frequency response

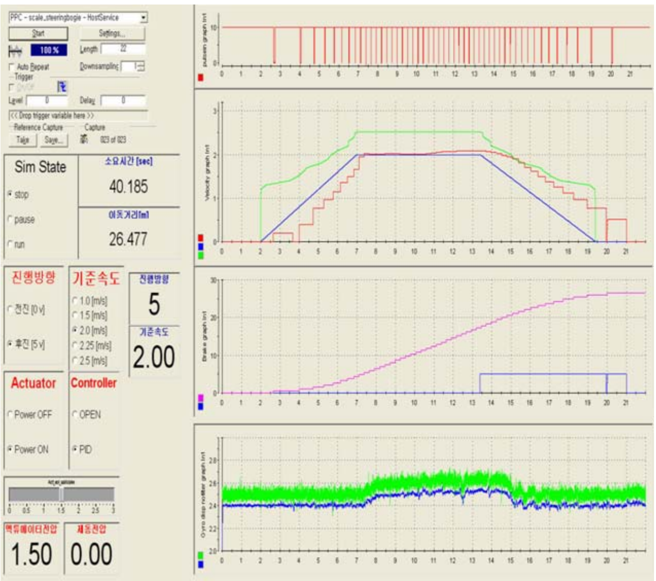


(b) Frequency response

Fig.21 Frequency response analysis of the steering bogie

C. *Test Results of Curving Running*

A curve track with R=20[m] and 27.11[m] length is considered for a running test of the scale model. The steering bogie of the vehicle model was driven by the driving bogie at 2 [m/s] speeds. Fig. 22 shows the experimental results of the pulse train of the number of rotations, the vehicle speed, the moving distance, and the gyro sensor signals, respectively.

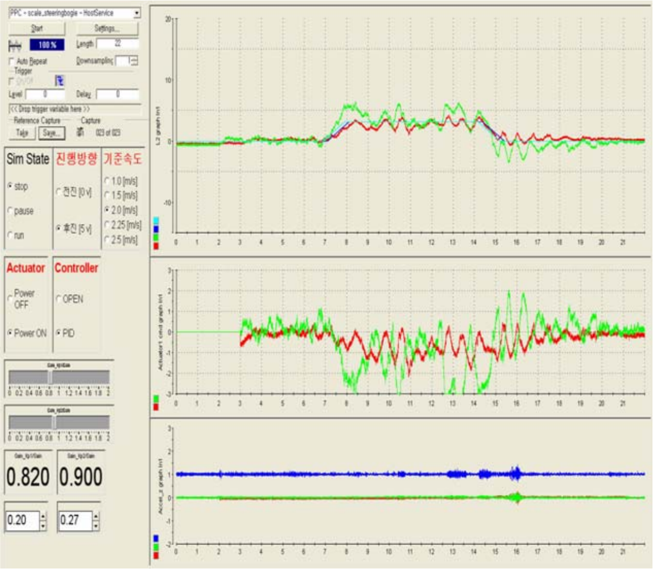


PPC - scale_steeringbogie - HostService
Length 22
Level 0
Delay 0
Capture 023 of 023

Sim State ● stop ○ pause ○ run
소요시간 [sec] 40.185
이동거리[m] 26.477
진행방향 ○ 전진 [0 V] ● 후진 [5 V]
기준속도 ○ 1.0 [m/s] ○ 1.5 [m/s] ● 2.0 [m/s] ○ 2.25 [m/s] ○ 2.5 [m/s]
진행방향 5
기준속도 2.00
Actuator ○ Power OFF ● Power ON
Controller ○ OPEN ● PID
엑츄에이터전압 1.50
제동전압 0.00

Fig.22 The experimental results: the pulse train, the vehicle speed, the moving distance, and the gyro sensor signals

The experimental results of the relative displacement, the actuator command voltage, and a characteristic vibration of carbody are shown in Fig. 23, respectively.

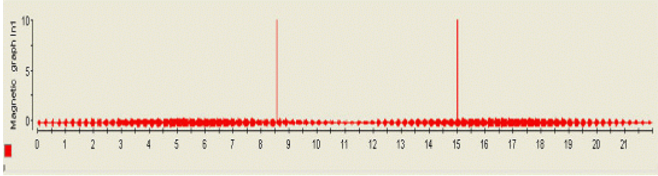


PPC - scale_steeringbogie - HostService
Length 22
Level 0
Delay 0
Capture 023 of 023

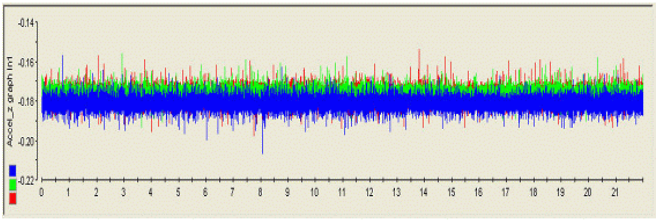
Sim State ● stop ○ pause ○ run
진행방향 ○ 전진 [0 V] ● 후진 [5 V]
기준속도 ○ 1.0 [m/s] ○ 1.5 [m/s] ● 2.0 [m/s] ○ 2.25 [m/s] ○ 2.5 [m/s]
Actuator ○ Power OFF ● Power ON
Controller ○ OPEN ● PID
0.820 0.900
0.20 0.27

Fig.23 The experimental results: the relative displacement, the actuator command voltage, and a characteristic vibration of carbody

Fig. 24 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 carbody.



(b) Magnetic sensor output



(c) Accelerometer output

Fig.24 The experimental results: various sensor outputs

V. CONCLUSIONS

In urban transit systems, rail passenger vehicles are often required to negotiate 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.

In this paper, we present the construction of active steering control system for the curving performance analysis. 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 testbed for active steering control system 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.

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