Journal of Mechanical Science and Technology 22 (2008) 2171~2179

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0722-0

Development of a tilting system for electric multiple unit to speed up on conventional lines †

Sung Il Seo[1,*], Nam Po Kim[2], Soo Gil Lee[2] and Seok Won Kim[1]

[1]*Director, R&D Policy Development Division, Korea Railroad Research Institute, Uiwang, Kyonggi, Korea*
[2]*Principal Researcher, Tilting Train Engineering Corps., Korea Railroad Research Institute, Uiwang, Kyonggi, Korea*

(Manuscript Received February 20, 2008; Revised July 7, 2008; Accepted July 22, 2008)

Abstract

An advanced tilting system for KTT (Korean Tilting Train) was developed and a performance test of the system has been completed. KTT has been constructed to speed up and promise a significant enhancement in service quality on a conventional line. KTT is an electric multiple unit composed of 6 cars running at the design speed of 200 km/h. The tilting system is the core technology of KTT and combined with the conventional bogie system. It has a self-steering mechanism and a swing link. The self-steering mechanism of Z-bar type is free to rotate on the curve and stable to run on a straight line. The swing link mechanism of the bolster enables the carbody to tilt up to 8° . A tilting control system detects a curve with sensors and commands the electro-mechanical actuators to move the bolster through the computer network system. GPS collaborates with the tilting system to perceive the curve previously and enables gradual tilting so as not to violate passenger comfort. The performance of the tilting system has been verified by a trial test running of KTT on a commercial conventional line. The tilting system is ready for commercial use.

Keywords: Conventional line; Curve, Electric multiple unit; Electro-mechanical actuator; Speed-up; Self-steeringmechanism; Swing link; Tilting control system; Tilting train

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1. Introduction

As much as 70 percent of Korea is covered with hills and mountains. Therefore, many curves are located on conventional lines that have kept trains from speeding up. Conventional passenger trains have been running at 140 km/h for twenty years in Korea. For speed-up of the railway system, a new high speed line has been constructed and KTX (Korea Train eXpress) started commercial service at the operating speed of 300 km/h. For KTX to maintain this speed, a straight line is indispensable and many tunnels and bridges must be constructed on the new high speed line. However, enormous construction cost for a high speed line impacts the national economy and serious damage to the environment causes severe problems. Also, for balanced development of the nation, citizens living in the regions other than the newly built high speed line must be satisfied with the benefits from the railway service more than the conventional passenger train. These problems can be solved by a fast railway system for conventional lines. The tilting train, which has been a candidate for the railway system, can accomplish speed-up on conventional lines without construction of new high speed lines.

Therefore, advanced countries have started to develop the tilting train system. Since the first tilting train was developed in the UK in 1978, several tilting train systems have been proposed [1]. A passive pendulum type tilting system was proposed in the early stage. The carbody is free to rotate laterally on a curve and centrifugal force is balanced with the carbody weight in the tilting position. However, originally, excessive vibration was a serious obstacle to

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† This paper was recommended for publication in revised form by Associate Editor Hong Hee Yoo

*Corresponding author. Tel.: +82 31 460 5623, Fax.: +82 31 460 5139
E-mail address: siseo@krri.re.kr

popular commercial use. An active tilting system began to be applied to overcome the excessive vibration problem. A pneumatic actuating system has been used for active tilting control, but to supply more powerful and stable force, a hydraulic actuating system began to be applied. However, the hydraulic system also occupied large space and accurate control was difficult. So, a safer and more reliable tilting system has been needed for the advanced tilting train system.

In this paper, an advanced tilting system for speed-up on conventional lines is introduced. It is the core system of KTT. A prototype tilting system has been completed by original technologies and its performance was verified by trial tests. An electro-mechanical actuating system, self-steeringmechanism, swing link and tilting control with GPS (Global Positioning System) are the major characteristics of the tilting system. The function and operational principle is presented and testing results are shown. Also, major achievements of KTT system are introduced.

2. Korea tilting train system

The KTT is an express train connecting the cities on the conventional line faster and more comfortably than a conventional train. KTT is a tilting train of EMU (electric multiple units). When KTT encounters a curve, it tilts the carbody toward the inside of the curve to counter the centrifugal force. Fig. 1 shows the principle of a tilting train. Since a cant on the curve is based on the average speed of passing trains, it is not sufficient for a high speed train. Therefore, for a passenger on the high speed train not to feel the lateral movement, the deficiency of cant is compensated by the tilting angle [2]. The passengers would not sense any lateral motion in the cabin, theoretically, if the required tilting angle is provided as shown in Fig. 1. The resultant force of centrifugal and gravity forces is acting normal to the floor.

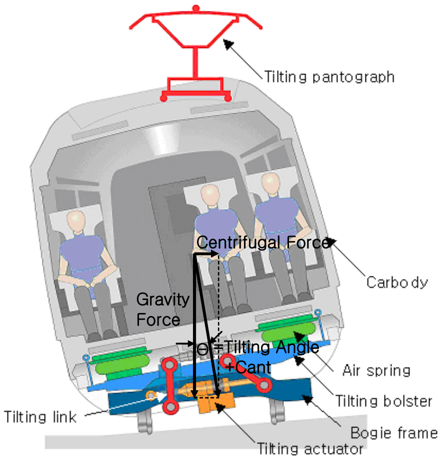


Fig. 1. Carbody tilting induced by actuators.

KTT was designed to run on the conventional line at the design speed of 200 km/h to come up with the improved infrastructure composed of track, catenary and signaling system [3]. The speed limit of the infrastructure on the first graded conventional line in Korea is 200 km/h [4]. Fig. 2 shows KTT waiting for a start on the conventional line and Table 1 gives the major information of KTT.

Most inter-city trains in Korea are driven by the power cars. KTX is also pushed and pulled by the first and last power cars. However, KTT is driven by distributed motors on the bogies and formed of an electric multiple unit which has large adhesive traction effort and good accelerating performance. In the

Table 1. Major information of KTT.

Information	Value
Design speed (Maximum operating speed)	200 km/h (180km/h)
Train power system	Electric Multiple Unit
Train formation	6 Cars (2 Motor cars +2 Trailers+2 Motor Cars)
Weight (full load)	344 tons
Maximum axle load	15 tons
Total Length	143 m
Breadth× Depth (from rail top)	2.97m×3.69m
Number of motors (Traction power)	16 (250 kW per motor)
Number of pantographs	2
Material of bodyshell	Composite honeycomb sandwich panel + Stainless steel(Underframe)
Number of seats	278 (First class 29 seats, Second class 56 seats)

Fig. 2. KTT on the conventional line.

Table 2. Weight of bodyshell.

Structure	Weight		Remark
	Stainless Steel bodyshell	Hybrid bodyshell	
Upper Carbody	70.7 kN	43.4 kN	Reduction by 39 %
Underframe	45.7 kN	40.8 kN	
Total	116.4 kN	84.2 kN	
Ratio(weight)	1	0.72	

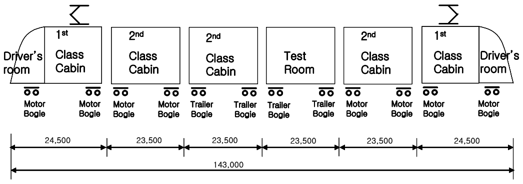


Fig. 3. Trainset of KTT.

conventional line, accelerating and decelerating performance is critical to reduce the running time among the close stations. A train of EMU has good accelerating performance and can be formed flexibly. Cars can be added or removed as needed. The trainset of a prototype KTT is formed of four motor cars and two trailers as shown in Fig. 3.

KTT was designed to be as light as possible, because light weight is profitable for speed-up and reduction of wheel load. When the wheel load becomes less, the maintenance work for the track is reduced. For weight minimization, the bodyshell of KTT was designed to be made of composite material [3]. The upper bodyshell is composed of composite honeycomb panels and the lower underframe of stainless steel. The hybrid structure makes it possible to reduce the carbody weight by almost 28 %. Weight saving due to material change is shown in Table 2 [5]. The wheel load is reduced by 10 %, for equipment and passenger weights were added to the carbody weight.

The mission of KTT is to reduce travel times on the conventional line, which can be accomplished by speed-up on the curves. The maximum speed to be attained by the tilting effect depends on the radius of curve and the cant. Fig. 4 shows the possible speed-up on the curve at each radius of curve when the cant is constant [6]. A speed-up of 40 percent can be attained thanks to the tilting effect. For the candidate lines, train performance simulation was conducted and the benefit of KTT is presented as shown in Table 3 [7]. The traveling time is expected to be reduced by about 20% thanks to speed-up on the curve.

Table 3. Train performance simulation results for major routes.

Route	Train	Traveling Time(min)	Cut-off Time Percentage (%)
Joongang Line(Cheongryangri-Andong)	Saemaul	189	18.7
	KTT	159	
Kyeongbu Line(Seoul-Busan)	Saemaul	276	19.0
	KTT	232	
Honam Line(Yongsan-Mokpo)	Saemaul	263	21.8
	KTT	216	
Jeolla Line(Yongsan-Yeosu)	Saemaul	306	21.4
	KTT	252	
Kyungjeon Line(Seoul-Jinju)	Saemaul	349	21.4
	KTT	293	

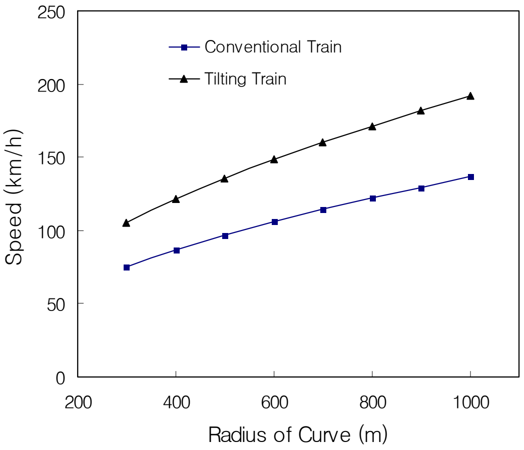


Fig. 4. Speed limits on curves.

3. System break-down of korea tilting train

KTT systems can be broken down as shown in Fig. 5. Most such systems are the same as those of EMU, since KTT is a kind of EMU. But the bogie and vehicle tilting system is different. It is the tilting system developed in this study and can be broken down into subsystems such as trailer bogie and motor bogie. A motor bogie is the same as a trailer bogie except for including traction motors. The trailer bogie is composed of LRUs (line replaceable units) shown in Fig. 5. Among the LRUs, carbody tilting electronics, carbody actuators, tilting bolster, wwing link and sensors are the major units that comprise the tilting system.

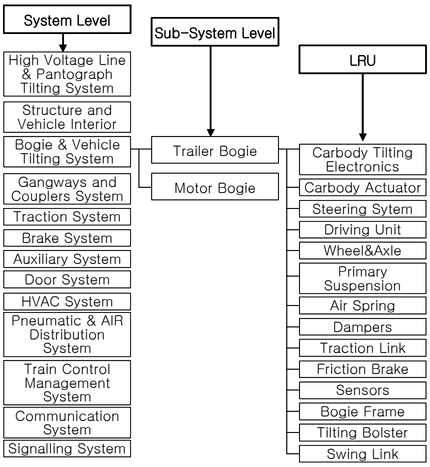


Fig. 5. System break-down of KTT.

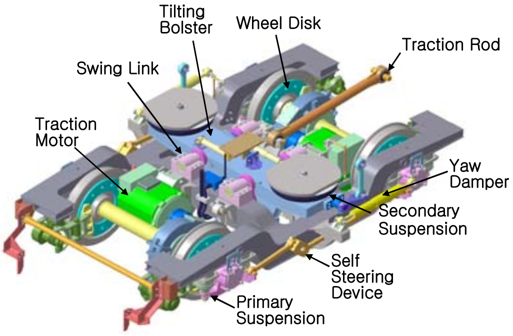


Fig. 6. Solid model of bogie system.

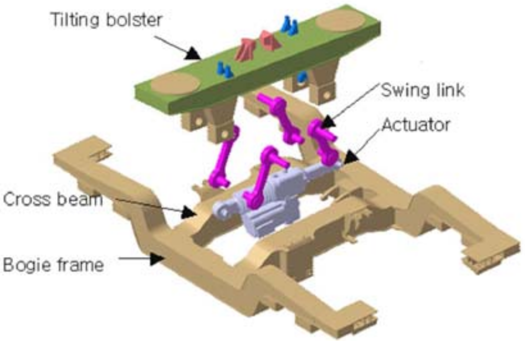


Fig. 7. Actuator to rotate tilting bolster through swing link.

4. Bogie system

Fig. 6 shows a solid model of the tilting bogie system with the composing units. The KTT carbody is supported on a tilting bolster, which is connected to the bogie frame through swing links. As the electromechanical actuator driven by the motor pushes or pulls the arm of the tilting bolster, the swing link enables the tilting bolster to rotate as shown in Fig. 7. A traction rod, which acts as the center pivot for the conventional train, transmits the traction force of the bogie to the carbody and is twisted with the end hinges during carbody tilting.

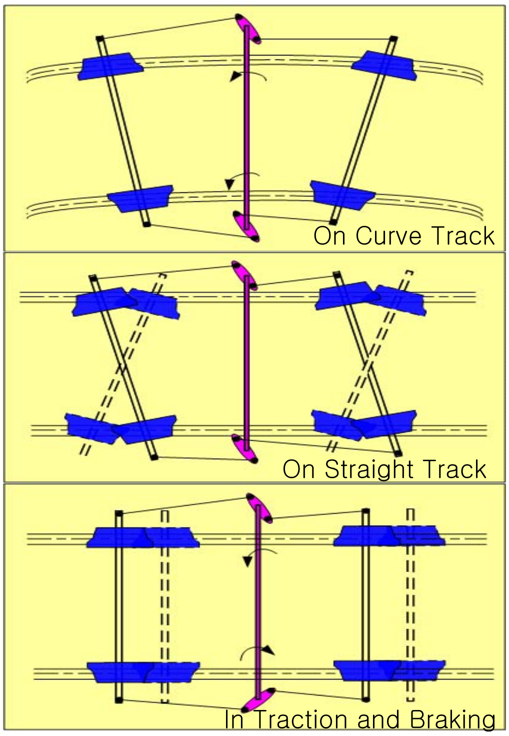


Fig. 8. Principle of self-steeringmechanism.

A self-steering mechanism on the bogie mitigates the lateral forces exerted by the wheels. Fig. 8 shows the principle of the self-steering system. A z-type bar helps the wheels to be expanded freely; however, on a straight track it restricts the wheels not to cause a relative angular motion with the aid of the cross bar. Also, in traction and braking, the cross bar exerts torsional moment and keeps the wheels to be straight.

Braking force to decelerate KTT is generated by both the electric and mechanical braking system. The electric traction system is converted to a generator when a braking command is issued. Regenerated electric power is transferred to the power station through the catenary system. Electric traction system takes the dominant part in decelerating KTT at high speed; however, the mechanical pneumatic braking system finally stops the KTT. Regenerative braking begins to work at a speed of 10km/h. Disks on the axle contact with the pad and generate friction braking force in the trailer bogie. However, a wheel is used for the braking disk in the motor bogie because of space limit, as shown in Fig. 6. The braking disk is made of CV NCM cast iron to keep strength up and cost down [8]. A sintered brake pad was developed to provide an optimum combination with the braking disk. The friction characteristics of the brake pad were determined to produce the required braking force at each speed and not generating hot spots.

5. Tilting control system

The electro-mechanical actuators driven by motors move the carbody on the bolster to tilt up to 8°. The tilting control system is shown in Fig. 9. The bogie sensor detects the lateral acceleration of the bogie system and the sensor detects the speed and position of the carbody. The transition zone before a curve is detected by these sensors. The signals from the sensors are transferred to the TTP (train tilting processor) through CAN (controller area network) communication. TTP calculates the optimum tilting condition on the basis of the information such as train speed, lateral acceleration, radius of curve and cant deficiency transferred from TMS. TMS communicates the tilting information with TTP. TTP issues the tilting command to CTE (carbody tilting electronics) on each bogie system with a time delay, so as to tilt the carbodies sequentially as each vehicle enters the curve. CTE controls the actuating motor and the control unit to move the links in the bogie. CTE of the front carbody communicates a tilting command with CTE of the next carbody through RS422 network lines.

GPS receives the position data continuously and sends it to TTP. TTP has the line data previously recorded and perceives the curve before entering it by comparing the position data. TTP issues a tilting command ahead of the curve following the same procedure mentioned above. The carbody tilts gradually while passing the curve and passengers do not feel any harmful lateral motion. The tilting control system by using GPS is a supplementary system to collaborate with the sensor detection system. Tilting roll rate by the senor detection is 0.5 degree/sec; however, the tilting roll rate by GPS is 0.3 degree/sec.

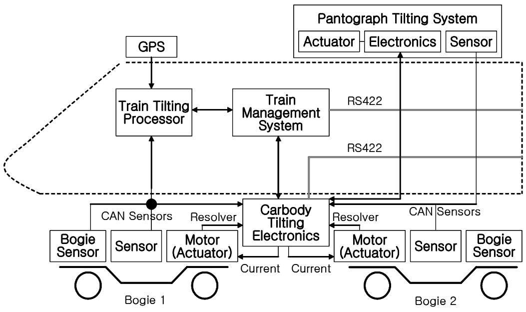


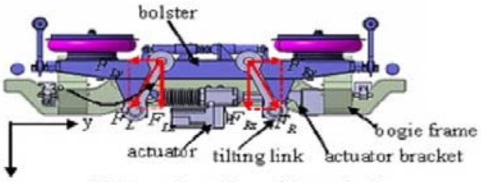
Fig. 9. Schematic diagram of tilting control system.

As the train tilts through a curve, the pantograph must tilt in the opposite direction in order to maintain contact with the overhead line. The pantograph is mounted on a sledge on the roof, which is supported by rollers and guide rails. Tilting commands for the pantograph are issued by TTP simultaneously with those for the tilting bolster. CTE controls the PTS (pantograph tilting system) on the roof as well as the actuating motor for the carbody [9].

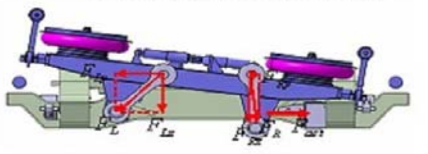
6. Test for bogie system

In order to verify the performance and safety of the tilting bogie system, various tests were conducted. First, structural loading tests were made for the bogie frame to evaluate the strength. Static load test and simplified strength evaluation were conducted. International standards suggest the ordinary static loads for the bogie frame [10, 11], but they do not suggest special loads due to tilting. The maximum load due to tilting was calculated by multi-body dynamic analysis using the special software [1]. Fig. 10 shows the loads acting on the links during maximum tilting. The maximum tilting loads as well as the ordinary static loads were applied to the bogie frame and the stresses were measured. Fig. 11 shows Goodman's diagram to evaluate the strength of the bogie frame based on the criteria [10]. It verifies the structural safety of the frame for the maximum load. Second, a dynamic load test was conducted to prove the safety against fatigue failure. Fig. 12 shows the prototype bogie frame under dynamic loading test. The actuators exert vertical and lateral forces on the frame following the loading history. While vertical weight and tilting load were acting, dynamic fluctuating loads were added as shown in Fig. 13. After 1×10^7 loading cycles were finished, fatigue failure was investigated by the liquid penetration and magnetic particle test. There was no failure and the frame was proven to be safe against the dynamic loads.

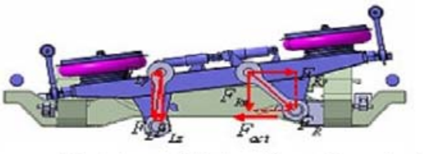
Finally, to verify the safety of the bogie system on the commercial line, dynamic running tests were conducted on the roller rig as shown in Fig. 14. The complete bogie system was combined with a dummy



(a) Normal position of the carbody

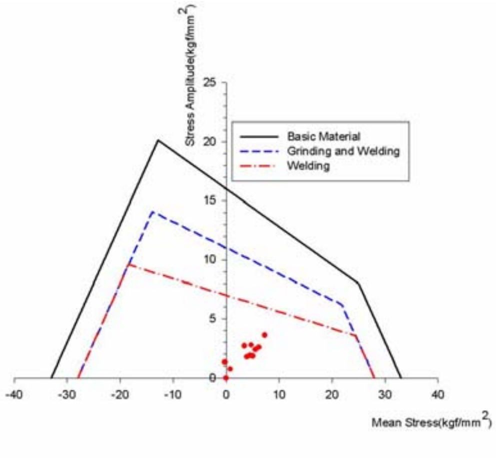


(b) +8 degrees tilted position of the carbody



(c) -8 degrees tilted position of the carbody

Fig. 10. Tilting loads on swing links.



Bogie frame under tilting condition (UIC)

Fig. 11. Goodman's diagram for strength evaluation.

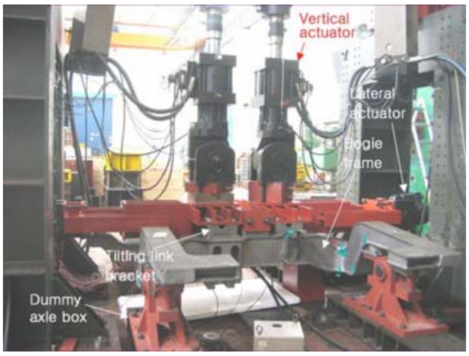


Fig. 12. Bogie frame under dynamic loading.

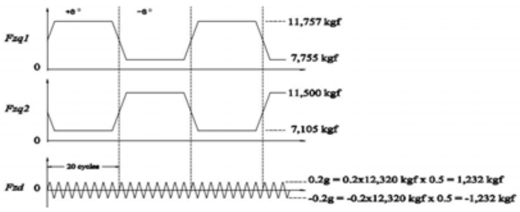


Fig. 13. Dynamic loads for testing.

Fig. 14. Bogie system under roller rig test.

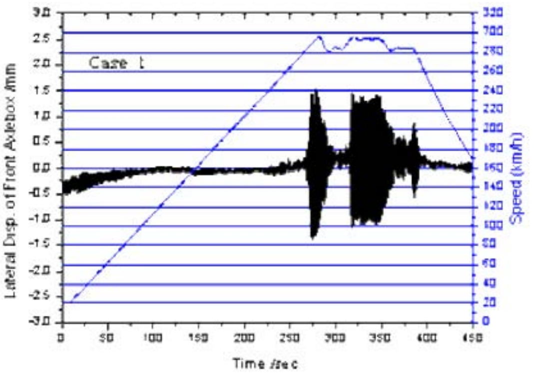


Fig. 15. Result of dynamic running test on roller rig.

carbody with the same mass and inertia. The roller rig began to speed up until the hunting speed of the bogie system was attained. Fig. 15 shows the results of the roller rig test. The bogie system was stable up to 280 km/h, which is more than the design speed of 200 km/h [12]. It verifies that the bogie system has running stability.

7. Test for tilting system

To verify the tilting performance of KTT, static and dynamic tests were conducted. The authors proposed six test items for verification of tilting performance.

Table 4. Test results for tilting performance.

Test Item	Objective	Test Result	Condition
Moving direction of actuators	To check whether all the actuators move in the same direction	OK	Static Test
Clearance and gauging	To check the gauging of apparatus against the vehicle limit and the clearance between devices in tilting mode	No touch with the gauging template in extreme tilting condition	Static Test
Verification of tilting command	To check whether the calculated tilting angle is consistent with the commanded tilting angle and the actual tilting angle	The calculated tilting angle was exactly the same with the commanded tilting angle. The actual tilting angle was within 5 % error bounds with the commanded tilting angle.	Static and Dynamic test
Demonstration of delay between cars	To check the delay of the tilting commands between cars and confirm the reaction of car	The measured tilting starting time in the next car was exactly after the time delay	Static and Dynamic
Demonstration of auto-centering of tilting system	To demonstrate auto-centering of the tilting system in emergency condition	The carbody was auto- centered in response to an emergency signal	Static and Dynamic
Demonstration of passenger comfort	To demonstrate passenger comfort during tilting operation	Measured riding comfort was below the critical comfort level.	Dynamic Test

The test items and the results are presented in Table 4. First, to check whether all the electro-mechanical actuators move in the same direction, moving direction of the actuators was confirmed. If an actuator moves a carbody in the opposite direction to the tilting command, the carbody undergoes a twist and the tilting mechanism may fail due to extraordinary loading condition. Also, to prevent collision with the opposite train or the infrastructure component, the gauging of apparatus against the vehicle limit had to be checked. A gauging template was made and passing test was conducted. While the carbody was going through the template in extreme tilting angle, touching of an apparatus with the template was examined. Fig. 16 shows the test process. There was no touching with the template.

The calculated tilting angle by TTP must be consistent with the commanded tilting angle by TMS and the actual tilting angle. To verify the consistency, the tilting command signal was compared with the calculated tilting angle and the difference was checked. Also, the actual tilting angle was measured in each carbody and compared with the commanded tilting angle.

The carbodies tilt sequentially, as they enter a curve. To demonstrate a delay between cars, the tilting command and the reaction time was measured and verified. In emergency condition such that the tilting system fails, the carbody must be centered automatically so as not to create a hazard. An auto-centering test was conducted and the function was confirmed. Finally, in order not to detract from passenger comfort during the tilting operation, the acceleration on the cabin was measured and evaluated. There was no harmful accelerating motion.

Fig. 16. Clearance and gauging test.

8. Trial test run

The prototype KTT finished test running on the commercial line. During running, the performance of the tilting system was monitored and verified by the total measurement system shown in Fig. 17. A digital camera on the roof monitored the tilting pantograph and transmitted the image data to the total measurement system. The vibration of the bogie system was measured and evaluated. The accelerometers were attached to the frame to sense the vertical and lateral vibration. The measured acceleration showed the bogie system was stable over the design speed range. On the cabin, vibration levels were measured to evaluate riding quality during tilting. Fig. 18 shows

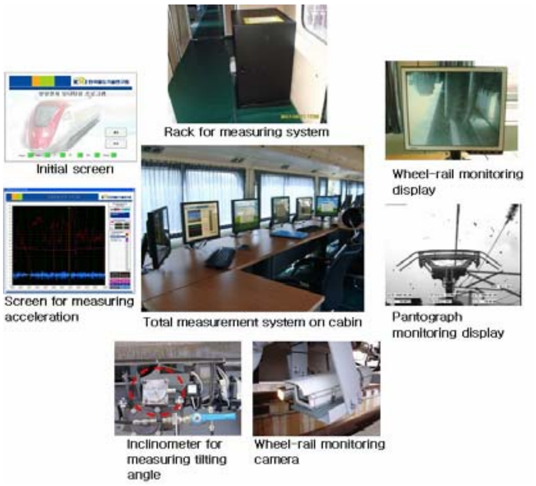


Fig. 17. Total measurement system in test room.

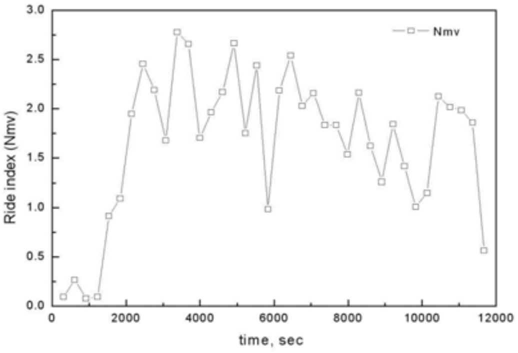


Fig. 18. Test results for riding quality.

the results. The riding quality was below 2.8, which indicates that good riding comfort.

9. Conclusion

A tilting train is the most economical and easiest means for speed-up on conventional lines. The tilting system is the core technology in the tilting train. In this study, a unique tilting system was developed and its performance was proven by tests and trial runs. The self-steeringmechanism of Z-bar type composing the bogie system is free to rotate on a curve and stable to run on a straight line. The stability and running performance was verified by a roller rig test. The swing link mechanism of the bolster enables the carbody to tilt up to 8º. The structural safety of the bogie frame was verified by static and dynamic loading tests. A novel tilting control system was developed and the performance was proven by the proposed test procedure. Previous detection of a curve using GPS and gradual tilting of the carbody enhanced passenger comfort. A total measurement system was constructed to measure the overall performance and to monitor each device. KTT has finished test running on the conventional line and proven to run safely. It passed the certification process for a commercial train. After a reliability test is completed, the train is ready for commercial service. KTT will be able to replace the diesel-powered conventional passengers trains.

Acknowledgment

This research has been supported by Ministry of Construction and Transportation.

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SUNG IL SEO, Dr. Seo was born at Seoul, Korea in 1962. He graduated from Department of Naval Architecture, Seoul National University in 1984 and received a doctor degree from the same university in 1994. He entered Hanjin Heavy Industries Co. in 1986 and was engaged in structural design of ship and development of aluminum rolling stocks. He transferred to KRRI in 2002. He was engaged in development of Korea High Speed Train. He has been in charge of the development project for Korea Tilting Train. He published many research papers on high speed train, structural design and welding deformations in international journals.