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A study on the critical speed of worn wheel profile using a scale model †

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Abstract

A study was conducted to analyze the influence of wheel profile wear on running stability by using a 1/5 scale bogie model. The critical speed was analyzed by constructing a dynamic model for the bogie model. And the 1/5 scale bogie and a scaled roller rig prototype were manufactured to verify the feasibility of applying the scale model; a critical speed test was conducted for worn wheel profile samples. The test results for the scale model were consistent with the simulation results for the scale model within the range of 5% or less. Also, the variation of the critical speed of the scale model for the wheel profile wear shows a similar trend with the analysis results of the full scale model. Therefore, using the scale model to analyze the influence of wheel profile wear on running stability shows sufficient feasibility as a model to analyze the stability of a full scale bogie.

***Keywords*:** Critical speed; Scale bogie; Wear; Wheel profile; Scaled roller rig

1. Introduction

To secure the safety of a running, the stability of the bogie should be secured. Generally, a bogie stability test in the laboratory is implemented by using a roller rig [1]. The roller rig is composed of two rollers equivalent to the rails. It is used to test the limited performance of the bogie in areas such as the critical speed, or for the dynamic characteristics of the vehicle such as ride comfort through the rolling contact movement between the wheel and roller.

But tests that use a full scale roller rig to analyze the dynamic characteristics, with real bogie, can be costly and the test preparation can be time consuming. To overcome these shortcomings, a scale model which is very effective in terms of test convenience is used.

To use the scale model, a similarity law is applied. The similarity law and scale factors are different according to the purpose of using the scale model. Iwnicki used the scale model for the purpose of studying the stability and dynamic characteristics of vehicles by using the same materials and focused the point of similarity on frequency [2]. Pascal implemented a scaled, large diameter roller to study the creep theory and contact dynamics of wheels and rails, and focused the point of similarity law on the velocity [3]. Jaschinski used the scale model to verify the feasibility of multi-body dynamics theory and the nonlinear equation of motion, and tried scaling by focusing the point of similarity on acceleration [4, 5]. Bosso studied the differences among the similarity laws and compared test results with simulation results [6-8]. He also used the scale model to study vehicle brake characteristics [9].

As above, the feasibility of the scale model has been verified and used as an alternative to full-scale models in vehicle design and development stages. Therefore, in this paper, a scale model was used to analyze the influence of wheel profile wear on the

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vehicle stability. A 1/5 scale bogie and a scaled roller rig prototype were designed and manufactured to test the critical speed of the bogie. The critical speed of the bogie for wheel profile wear was analyzed, and critical speed test was conducted by using scaled samples of worn wheel profiles.

2. Wheel profile wear

We studied the subject of a wheel profile inclined 1/20 applied in the Korean Railway. The wheel profile is shown in Fig. 1. To analyze the wear characteristic of the wheel profile with increased distance traveled, initial wheel profile was referenced and re-profiled according to draft, and the shape of the wheel profile was measured regularly. The wheel profile was measured by MINIPROF Wheel Profile Gage of Greenwood Eng. as shown in Fig. 2. It was measured four times and the total distance traveled was 113,911km.

To analyze the variation of wheel profile, wheel dimension parameters such as flange thickness (FT), flange height (FH), flange angle (FA) and vertical wear factor (qR) as shown Fig. 3 were analyzed by comparing them to the initial profile. Fig. 4 shows the wear profile. It shows the wear occurred at flange compared with the initial profile as the mileage is increased. Table 1 shows wheel profile data and the variation of the wheel dimension parameters, which were measured four times. Fig. 5 shows the variation of the wheel dimension parameters. After 113,911km, the flange thickness of flange decreased to 30.56mm from 33.91mm, and the flange height increased to 28.32mm from 26.94mm. The flange angle, which means vertical wear of flange, increased to 71.07° from 63.9°, and qR decreased to 8.12mm from 11.02mm. Especially, in case of 2nd measurement, which is the initial stage of the test running, wheel dimension parameters such as qR and FA changed sharply. Therefore, it was discovered that changes of the wheel profile were severe due to wheel profile wear.

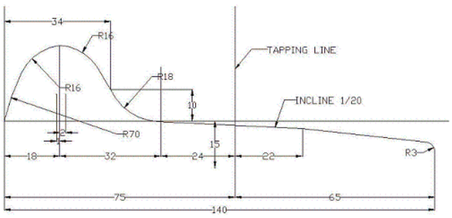


Fig. 1. Wheel profile for EMU.

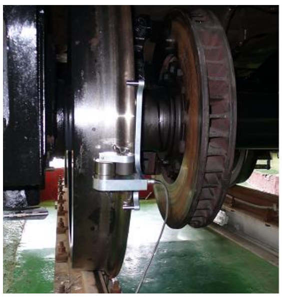


Fig. 2. Wheel profile gage.

Table 1. Test results of the wheel dimension parameters.

Measure-ment	wheel data	mileage (km)	FT (mm)	FH (mm)	qR (mm)	FA (deg)
1st	R11	0	33.91	26.94	11.02	63.90
2nd	R12	27,206	32.82	27.27	9.92	70.27
3rd	R13	60,878	31.54	27.9	8.31	73.04
4th	R14	113,911	30.56	28.32	8.12	71.07

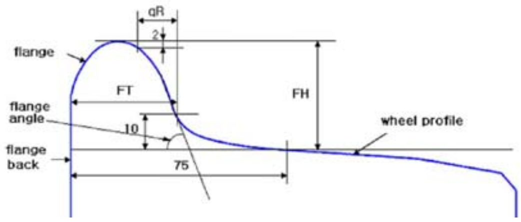


Fig. 3. Wheel dimension parameters.

Fig. 4. Wheel profile wear

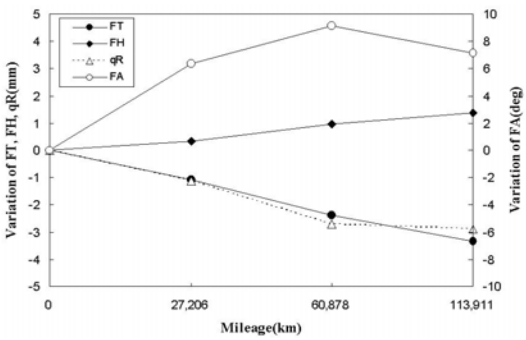


Fig. 5. Variations of wheel dimension parameters.

3. Dynamic model of a bogie

A dynamic model was established to analyze the critical speed of the bogie model for the wheel profile wear. The dynamic model is assumed as a 6-DOF model composed of one bogie on the roller rig as seen in Fig. 6. The wheelsets and bogie frame are allowed to move in lateral and yaw direction, and other movements are constrained. Eq. (1), Eq. (2), Eq. (4), and Eq. (5) show the force and moment equations of the wheelset, respectively, and Eq. (3) and Eq. (6) show equation of the bogie [10-12]. To calculate the creep forces at contact points, Oldrich Polach's algorithm was applied [13].

$$m\ddot{y}_1 = F_{Ly1} + F_{Ry1} + F_{Ly1} + F_{Ry1} + F_{s1} - m_w g\phi_1 \quad (1)$$

$$my_2 = F_{Ly2} + F_{Ry2} + F_{Ly2} + F_{Ry2} + F_{s2} - m_w g\phi_2 \quad (2)$$

$$my_3 = F_{s1} + F_{s2} \quad (3)$$

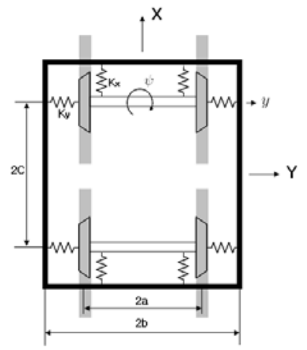
$$\begin{aligned} I_{wz}\ddot{\psi}_1 = &- I_{wy}(V/r_0)\dot{\phi}_1 + R_{Rx1}(F_{Ry1} + N_{Ry1}) \\ &+ R_{Lx1}(F_{Ly1} + N_{Ly1}) - R_{Ry1}F_{Rx1} - N_{Ry1}R_{Ry1} \\ &- R_{Ry1}F_{Rx1} + M_{Rz1} + M_{Lz1} \end{aligned} \quad (4)$$

$$\begin{aligned} I_{wz}\ddot{\psi}_2 = &- I_{wy}(V/r_0)\dot{\phi}_2 + R_{Rx2}(F_{Ry2} + N_{Ry2}) \\ &+ R_{Lx2}(F_{Ly2} + N_{Ly2}) - R_{Ry2}F_{Rx2} - N_{Ry2}R_{Ry2} \\ &- R_{Ry2}F_{Rx2} + M_{Rz2} + M_{Lz2} \end{aligned} \quad (5)$$

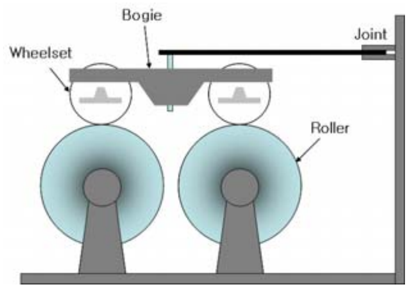
$$\begin{aligned} I_{bz}\ddot{\psi}_3 &= c(F_{s1} - F_{s2}) - (M_{s1} + M_{s2}) \\ F_{s1} &= 2K_y(-y_1 + y_3 - c\psi_3) + 2C_y(-\dot{y}_1 + \dot{y}_3 - c\dot{\psi}_3) \\ F_{s2} &= 2K_y(-y_2 + y_3 - c\psi_3) + 2C_y(-\dot{y}_2 + \dot{y}_3 - c\dot{\psi}_3) \\ M_{s1} &= 2b^2K_x(-\psi_1 + \psi_3) + 2b^2C_x(-\dot{\psi}_1 + \dot{\psi}_3) \\ M_{s2} &= 2b^2K_x(-\psi_2 + \psi_3) + 2b^2C_x(-\dot{\psi}_2 + \dot{\psi}_3) \end{aligned} \quad (6)$$

where,

V : Velocity (m/s)
m_w : Mass of wheelset (kg)
m_b : Mass of bogieframe (kg)
I_{wy} , I_{wz} : Moment of inertia of wheelset (kgm^2)
I_{bz} : Yaw moment of inertia of bogieframe (kg m^2)
y_i : Lateral displacement of wheelset (m), i=1,2
y_b : Lateral displacement of bogieframe (m)
ψ_i : Yaw displacement of wheelset (rad), i=1,2



(a) Coordinate of bogie model



(b) Bogie model

Fig. 6. Dynamic model for critical speed analysis.

ψ_b : Yaw displacement of bogieframe (rad)
γ_0 : Radius of wheel at equibrium state (m)
a_i : Semi spacing between contact points (m), i=1,2
b : Lateral semi spacing of primary spring (m)
c : Bogie semi wheelbase (m)
$K_{x,}$: Longitudinal stiffness of primary spring (N/m)
$K_{y,}$: Lateral stiffness of primary spring (N/m)
$C_{x,}$: Longitudinal damping of primary spring (Ns/m)
$C_{y,}$: Lateral damping of primary spring (Ns/m)
F_{si} : Suspension force (N), i=1, 2
M_{si} : Suspension moment (Nm^2), i=1, 2
F_{Rxi} : Longitudinal creep force of right wheel (N), i=1, 2
F_{Lxi} : Longitudinal creep force of left wheel (N), i=1,2
F_{Ryi} : Lateral creep force of right wheel (N), i=1, 2
F_{Lyi} : Lateral creep force of left wheel (N), i=1, 2
M_{Rzi} : Creep moment of right wheel (Nm^2), i=1, 2
M_{Lzi} : Creep moment of left wheel (Nm^2), i=1, 2

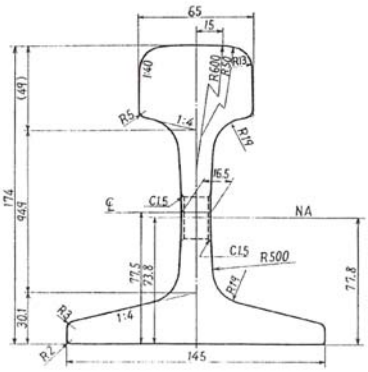


Fig. 7. Section of 60kg rail.

R_{Rxi} : Longitudinal contact position of right wheel (m), i=1, 2

R_{Lxi} : Longitudinal contact position of left wheel (m), i=1, 2

R_{Ryi} : Lateral contact position of right wheel (m), i=1, 2

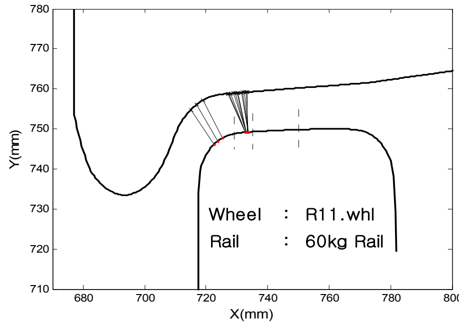
R_{Lyi} : Lateral contact position of left wheel (m), i=1, 2

4. Wheel/roller contact geometry analysis

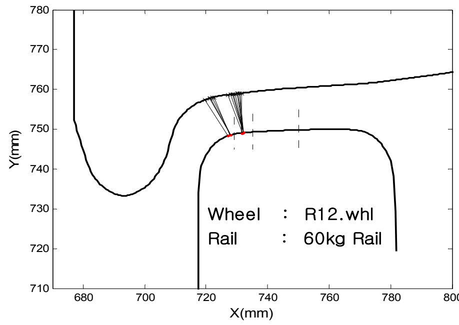
The creep force of the wheel/ roller is calculated before a numerical analysis of the critical speed. Therefore, a wheel/roller contact geometry analysis was conducted for the worn wheel profile samples ofTable 1. The head profile of the roller is 60kg rail profile inclined 1/40, and the wheel flange-back distance is 1,354mm, and gage is 1,435mm [14]. Fig. 7 shows the section of the 60kg rail.

Fig. 8 shows the contact patches from the wheel/ roller contact geometry analysis. In case of the first measured initial profile, Fig. 8(a), the contact points are distributed on a R50 curvature area of rail head profile seen in the Fig. 7. But in case of Fig. 8(d), the fourth measured profile, contact points are distributed around the area of gauge corner of rail head profile curvature R50 and R13. This transition of contact points distribution increases the rolling radius difference and finally increase equivalent conicity, which is defined as a half of the inclination of the rolling radius difference to wheelset lateral displacement.

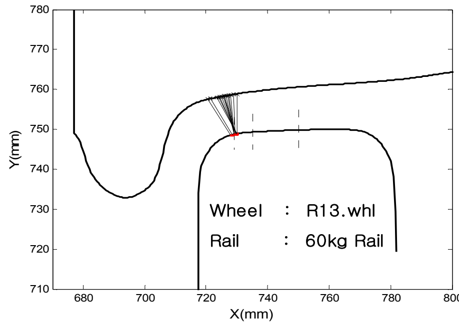
Fig. 9 shows the analysis results of wheel/roller contact geometry parameters to analyze the critical speed of the bogie model. As seen in Fig. 9(a), in case of rolling radius difference, the worse the wheel wear



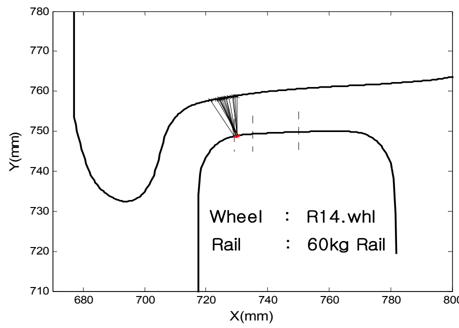
(a) R11



(b) R12



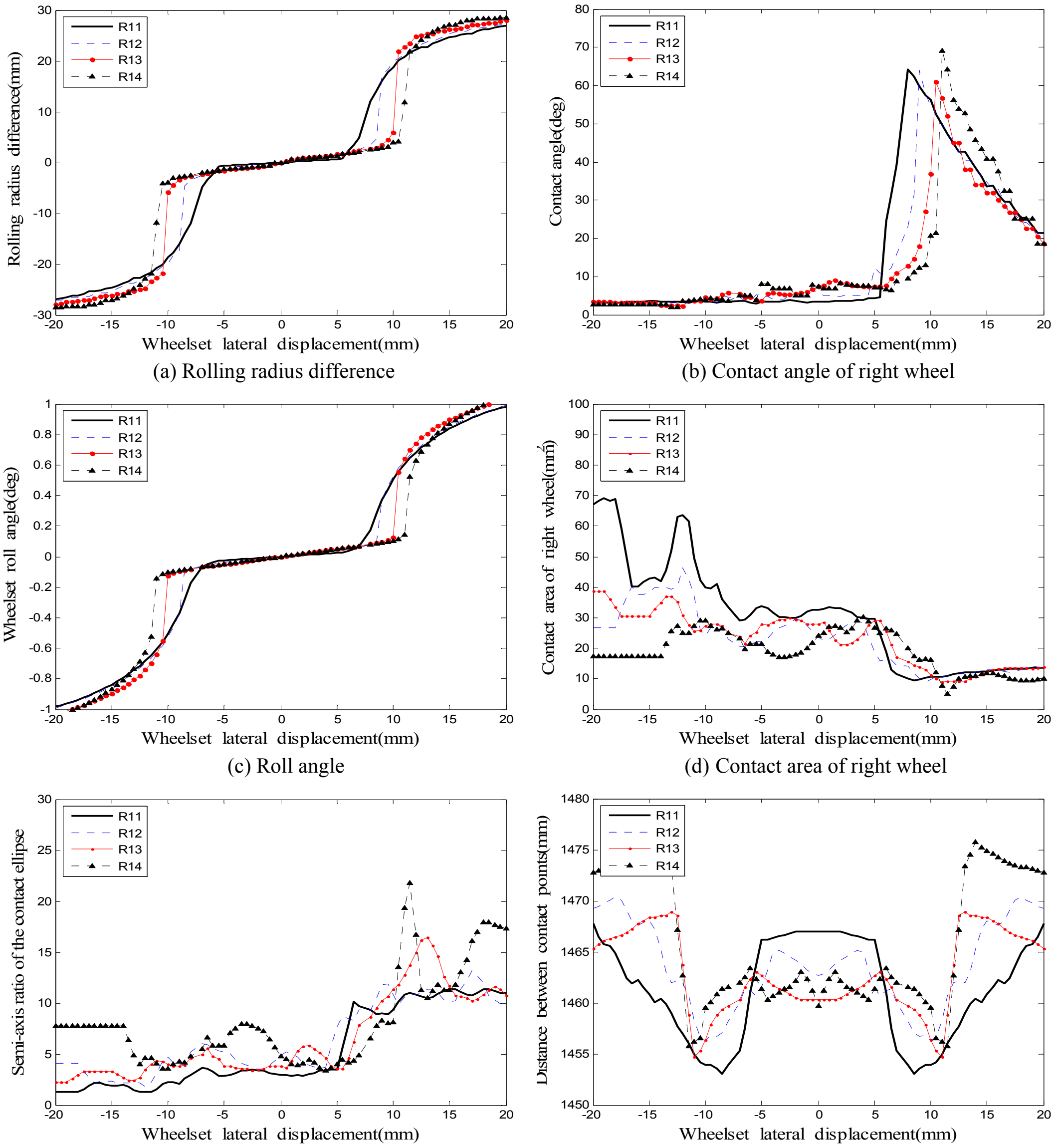
(c) R13



(d) R14

Fig. 8. Wheel/roller contact patch.

is, the greater the inclination is. Fig. 9(b) is the result showing contact angle of right wheel. As the wheel



(a) Rolling radius difference (b) Contact angle of right wheel

(c) Roll angle (d) Contact area of right wheel

(e) Semi-axis ratio of contact ellipse of right wheel (f) Distance between contact points

Fig. 9. Results of wheel/roller contact geometry analysis.

wear is severely preceding the contact angle for the lateral displacement of the wheelset is changed. Fig. 9(c) is the result of the wheelset roll angle, and it shows similar trend with rolling radius difference. Fig. 9(d) is the result showing contact area at the contact point of right wheel. It shows that the contact area of R14, wear profile, has lesser contact area than that of R11, initial profile. In case of the ratio of long and short semi axis at the contact ellipse shown in Fig. 9(e), R14 is bigger than R11. This means the shape of the contact ellipse is changed into a long, narrow ellipse according to the wheel wear. This change in the ratio of the long and short semi axis may influence the creep force at the contact point of wheel/roller. Fig. 9(f) is the result of the distance between contact points between left and right wheels.

5. Critical speed analysis

5.1 Full-scale bogie model

To analyze the variations of the critical speed of bogie for the wheel profile wear, a numerical simula-

Table 2. Specification of the full scale bogie model.

Parameter	Property
Mass of wheelset (kg)	1,680
Mass of bogieframe (kg)	2,150
Moment of inertia of wheelset (kgm^2): pitch/yaw	30/1,044
Yaw moment of inertia of bogie (kgm^2)	3,015
Stiffness of primary spring (N/m): x/y	6.7E6/4.9E6
Damping of primary spring (Ns/m): x/y	1E3/1E3
Lateral semi-spacing of primary spring (m)	1.0
Bogie semi wheelbase (m)	1.05
Wheel radius (m)	0.43
Roller radius (m)	0.75
Flange-back distance (m)	1,354
Gage (m)	1,435
Wheel profile	R11, R12, R13, R14
Rail profile	60kg rail profile
Young's modulus (N/m^2)	2.07E11
Gravity (m/s^2)	9.81
Wheel load (N)	48,850

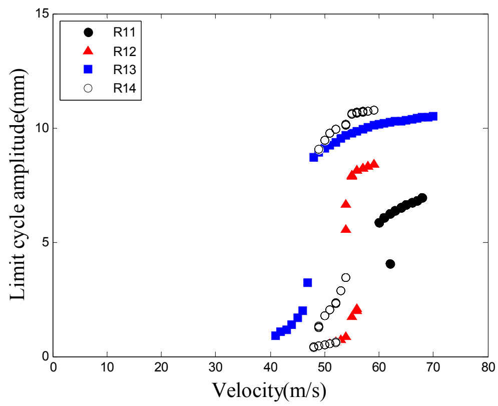


Fig. 10. Limit cycle diagram of the full-scale bogie model.

tion for the critical speed of the full scale bogie model was conducted. In this analysis, a non-linear hunting analysis method was applied [15]. Table 2 shows material properties of the full-scale bogie model.

Fig. 10 shows the limit cycle amplitude of the wheelset lateral displacement as a result of the critical speed analysis. In case of R11, the initial wheel profile, the critical speed was 60m/s, but in case of R12, it was 51m/s, and in case of R13 and R14, it was decreased to 41m/s and 43m/s, respectively. Comparing the critical speed of worn profiles (R12~R14) with the critical speed of initial profile (R11), the critical speeds of worn profiles (R12~R14) were decreased 15.0%, 31.7% and 28.3%, respectively.

5.2 1/5 scaled bogie model

An analysis of the critical speed of the 1/5 scale bogie model was conducted. The equations of motion for the scale bogie model are same as the equation of motion for the bogie model in Chapter 3. However, the scaling should be done by considering scaling factors such as dimension, mass and spring constant, etc.

If the index of the scale factor to full-scale model is "1," and the index of scale model is "0," each scale factor is as follows:

· length $\phi_l = l_1 / l_0$
· time $\phi_t = t_1 / t_0$
· cross section $\phi_A = \phi_l^2$
· volumn $\phi_v = \phi_l^3$
· acceleration $\phi_a = \phi_l / \phi_t^2$
· density $\phi_\rho = \rho_1 / \rho_0$
· mass $\phi_m = \phi_\rho \phi_l^3$
· moment of inertia $\phi_I = \phi_m \phi_l^2$
· inertial force $\phi_F = \phi_m \phi_a = \phi_\rho \phi_l^4 / \phi_t^2$
· stiffness $\phi_k = \phi_F / \phi_l = \phi_\rho \phi_l^3 / \phi_t^2$
· damping $\phi_c = \phi_F / \phi_v = \phi_\rho \phi_l^3 / \phi_t$
· modulus of rigity $\phi_G = G_1 / G_0$
· Young's modulus $\phi_E = E_1 / E_0$
· Poisson's ratio $\phi_\nu = \nu_1 / \nu_0$
· gravity $\phi_g = g_1 / g_0$

However, some factors such as gravitational acceleration and the modulus of rigidity are not applied by scaling law in this scaling process. And due to these parameters, some parameters were imperfectly applied by the similarity law among the parameters of equation of motion for the scale model. Especially, when calculating the creep coefficients related to the creep force at the wheel/roller contact point, errors related to the modulus of rigidity and wheel load occurred.

That is, the long semi axis and short semi axis of contact ellipse are functions of the modulus of rigidity and wheel load affected by gravity [12]. Therefore, if we assume that the similarity for the material property and gravitational acceleration is perfect (Case 1) and that the similarity for the material property and gravitational acceleration is not considered because the perfect application of similarity law is impossible (Case 2), each scaling factor for the creep coefficients is as follows:

Table 3. Specifications of the scale bogie model.

Parameter	Scale	Property
Mass of wheelset (kg)	$1/\phi^3$	13.5
Mass of bogieframe (kg)	$1/\phi^3$	17.2
Moment of inertia of wheelset (kgm^2): pitch/yaw	$1/\phi^5$	0.0096/ 0.334
Yaw moment of inertia of bogie (kgm^2)	$1/\phi^5$	0.965
Stiffness of primary spring (N/m): x/y	$1/\phi^3$	5.4E4/ 3.97E4
Damping of primary spring (Ns/m): x/y	$1/\phi^3$	125/125
Lateral semi-spacing of primary spring (m)	$1/\phi$	0.2
Bogie semi wheelbase (m)	$1/\phi$	0.21
Wheel radius (m)	$1/\phi$	0.086
Roller radius (m)	$1/\phi$	0.15
Flange-back distance (m)	$1/\phi$	0.271
Gage (m)	$1/\phi$	0.287
Wheel profile	$1/\phi$	R11, R12, R13, R14
Rail profile	$1/\phi$	60kg rail profile
Young's modulus (N/m^2)	1	2.07E11
Gravity (m/s^2)	1	9.81
Wheel load (N)		108.4

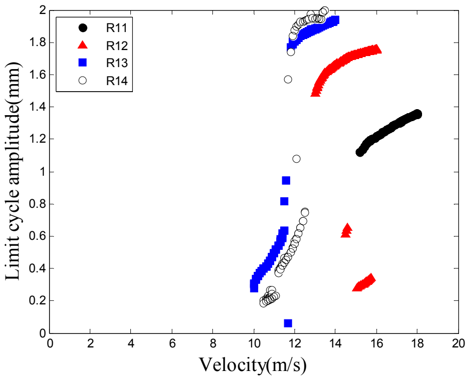


Fig. 11. Limit cycle diagram of 1/5 scale bogie model.

$\phi_t = 1$, $\phi_l = \phi$, $\phi_v = \phi$, $\phi_a = \phi$, $\phi_m = \phi^3$,
$\phi_I = \phi^5$, $\phi_k = \phi^3$

i) Case 1

$$\phi_g = \phi_l / \phi_t^2 = \phi , \quad \phi_E = \phi_N / \phi_l^2 = \phi^2 , \quad \phi_v = 1$$
$$\phi_{k1} = \phi_{k2} = 1/\phi_E = 1/\phi^2 , \quad \phi_{k3} = 1/\phi_l = 1/\phi$$
$$\phi_N = \phi^4 , \quad \phi_{\alpha\beta} = (\phi_N \phi_{K1} / \phi_{K3})^{2/3} = \phi^2$$
$$\phi_{f11} = \phi_{f33} = \phi^4 , \quad \phi_{f12} = \phi^5 , \quad \phi_{f22} = \phi^6$$

ii) Case 2

$$\phi_g = \phi_E = \phi_v = 1 , \quad \phi_{K1} = \phi_{K2} = 1/\phi_E = 1$$
$$\phi_{k3} = 1/\phi_l = 1/\phi$$
$$\phi_N = \phi^3 , \quad \phi_{\alpha\beta} = (\phi_N \phi_{K1} / \phi_{K3})^{2/3} = \phi^{2.67}$$
$$\phi_{f11} = \phi_{f33} = \phi^{2.67} , \quad \phi_{f12} = \phi^4 , \quad \phi_{f22} = \phi^{5.33}$$

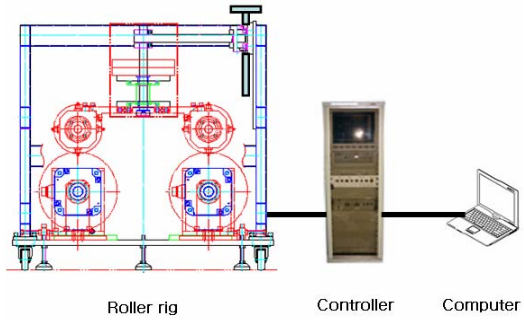


Fig. 12. Composition of experimental device.

As we know above scaling factors of case 2, the orders of $\phi_{f11}, \phi_{f12}, \phi_{f22}$ and ϕ_{f33} in relation to the creep coefficients are decreased compared with case 1.

Table 3 shows the specifications of the scale bogie model scaled to 1/5. The critical speed of the scale bogie model is analyzed by applying the specification of the scale bogie model in Table 3 and the scale wheel/roller contact parameter analyzed in Chapter 4. Fig. 11 shows the results of critical speed analysis on the scale bogie model for the wheel profile wear.

In the case of R11, the initial profile, the critical speed is 15.2m/s, and in case of R12, it is analyzed as 13.0m/s. In the case of R13 and R14, it is analyzed as 10.0m/s and 10.5m/s, respectively. Comparing the critical speed of worn profiles (R12~R14) with the critical speed of the initial profile (R11), the critical speeds of worn profiles (R12~R14) were decreased by 14.4%, 34.2%, and 30.9%, respectively.

6. Experimental device

To analyze the variation of the critical speed a 1/5 scale bogie model and scale roller rig were designed and manufactured as testing equipment. The wheel of the scale bogie is contacted on the roller equivalent to the rail, and it is rotated by friction force from driving roller axis. As seen in Fig. 12, it is composed of a roller rig, controller and computer. Table 4 shows the specification and features of the testing equipment. The major functions are as follows.

The roller is driven by two servo motors, and the section of the roller is shaped like a 60kg rail profile scaled down to 1/5. The head of the roller was inclined 1/40 by considering rail inclination. The roller

Table 4. Specifications of the experimental device.

Part	Specification
Roller rig	- 1/5 scaled roller rig type - dimension : 980mm × 680mm - roller radius : 0.15m - roller rolling : servo motor control - roller profile : 1/5 scaled 60kg rail - roller velocity : max. 2,000 rpm - variable wheel base : 400 ~ 500 mm - roller profile inclination: 0, 1/40 - roller lateral exciting : servo motor control frequency range: 1~10Hz exciting amplitude: ±3~±15mm
Controller	- hardware for roller rig control - interface between roller rig and computer roller velocity control with velocity profile roller lateral exciting - data acquisition system : I/O 24ch - sensor system velocity, acceleration, displacement include power supply for sensors
Computer	- include operating program - roller velocity control, lateral exciting control - measurement signal monitoring - emergency and normal stop

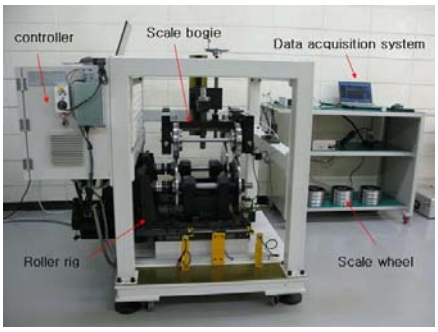


Fig. 13. Scale roller rig.

diameter is 0.3m, and the distance between left and right roller is the distance of a gage scaled down by 1/5. The distance between rollers is variable within 400mm~500mm to be in compliance with the wheel base of the scale bogie.

The lower base supporting the roller is movable laterally on the lower frame. The lower base is connected to a servo actuator composed of a servo motor and ball screw, and can be excited sinusoidally. This testing equipment makes it possible to simulate the lateral exciting of the roller rig to test bogie stability. Lateral motions equivalent to a sine wave, impulse and track irregularity are possible. The frequency range of the lateral exciting motion is from 1Hz

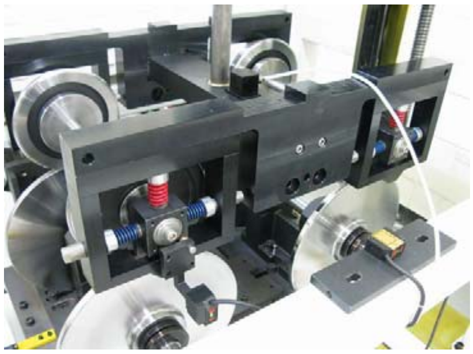


Fig. 14. Scale bogie.

(±15mm) to 10Hz (±3mm).

There is also a supporting device in the frame of the experimental device; it allows only the lateral and yaw motion of the bogieframe.

The controller performs a control function to control the servo motor and servo actuator of the roller rig, and data acquisition function to acquire measured signal from sensors. The roller rig operating program was installed in the computer, and it performs the following functions when connected to the controller. A velocity profile data of the servo motor to control the velocity of the roller and an input data file for the servo actuator for lateral exciting motion are created. If the roller velocity profile data and input data file for the servo actuator are selected and executed, the roller and base is driven. Also, the signals from sensors to measure the velocity of the roller and the behavior of the scale bogie can be monitored and saved as a data file. It includes an emergency stop which can stop the testing equipment in an emergency and a normal stop function. Fig. 13 shows the scale roller rig and experimental device.

The scale bogie was designed to 1/5 scale by applying the material properties in Table 3. A coil spring is applied for the primary suspension and in order to implement worn wheel profile, wheel prototype is manufactured by 1/5 scale of wheel shape equivalent to R11 ~ R14. Fig. 14 shows the prototype of the scale bogie.

The testing system is composed of scaled roller rig, scale bogie prototype, data acquisition system, and sensors. For the sensors, laser displacement sensor, accelerometer, and speed meter were used. The velocity of the roller, vibration of the scale bogie, lateral displacement of roller and bogie, and lateral displacement between wheelset and roller were measured.

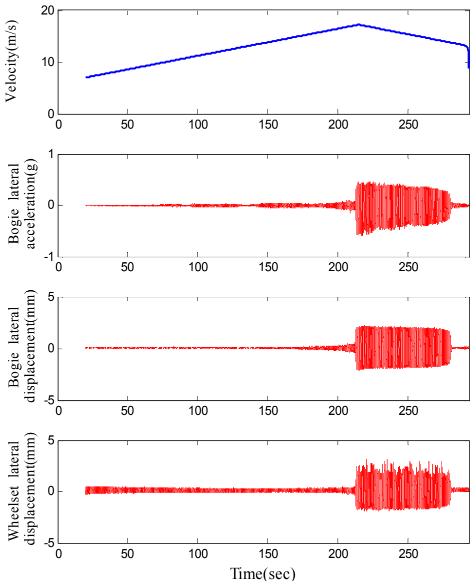


Fig. 15. Test data for R11 profile.

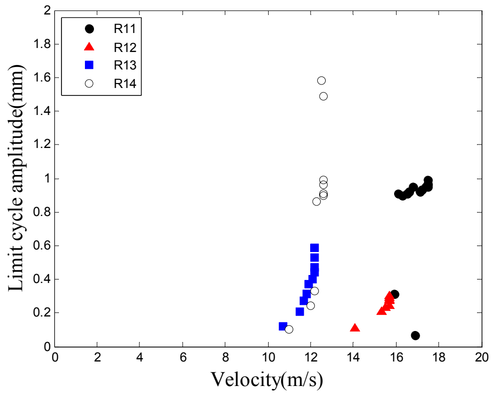


Fig. 16. Test data for the critical speed.

Table 5. Results of the critical speed analysis.

Wheel profile	Critical speed (m/s)			Variation of critical speed (%)		
	Simulation (full scale)	Simulation (1/5 scale)	Test (1/5 scale)	Simulation (full scale)	Simulation (1/5 scale)	Test (1/5 scale)
R11	60.0	15.2	15.9	100.0	100.0	100.0
R12	51.0	13.0	14.1	85.0	85.5	88.7
R13	41.0	10.0	10.7	68.3	65.8	67.3
R14	43.0	10.5	11.0	71.7	69.1	69.2

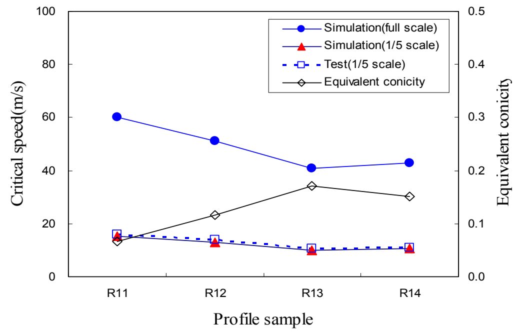


Fig. 17. Critical speed for worn wheel profiles.

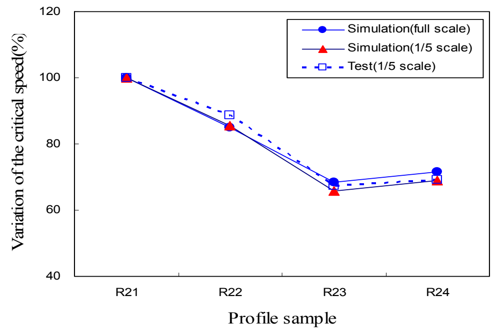


Fig. 18. Variation of the critical speed.

7. Critical speed test

A critical speed test was conducted by using the scale bogie and the test procedure is as follows. First, the scale bogie was set on the roller rig and supported by a supporting device to constrain the other motions of the scale bogie, excluding lateral and yaw motions. Next, the velocity of the roller was increased step by step, and the signal of each part of the scale bogie was monitored to analyze the stability.

There are two types of critical speed test; roller non-exciting test and roller exciting test. The purpose of the roller non-exciting test is to analyze the instability of the test subject by self-exciting motion according to increasing roller velocity, while the purpose of the roller exciting test is to analyze the instability of the test subject by lateral exciting motion of roller according to increasing roller velocity. In this paper, critical speed test was conducted by roller non-exciting test method.

Fig. 15 shows the example of the test data for the wheel profile R11. In this figure, the hunting phenomenon appears in which the motion of the wheelset was divergent with the increase of roller velocity and conversed with the decrease of roller velocity.

Fig. 16 shows the test results of the critical speed for the worn wheel profiles. In the case of R11, the critical speed is 15.9m/s, and for R12, it is 14.1m/s.

For R13 and R14, it is 10.7m/s and 11.0m/s respectively. Fig. 17 shows the relation between the critical speed and equivalent conicity, and Fig. 18 shows the variation of the critical speed for wheel profile wear. As seen in Fig. 17, the equivalent conicity is increasing with the increase of wheel flange wear and the critical speed is inversely proportion to the equivalent conicity.

Table 5 shows the results of the simulation and test for the full scale and 1/5 scale model. It is seen that the simulation results of the scale model correlate well with the test results of the scale model. Especially, the result of the variation of the critical speeds shows that the simulation results of the full scale model correlate quite well with the simulation and test results of the scale model. Also, the maximum error between the simulation and test results is less than 5%, so the construction of a dynamic model and numerical analysis to evaluate the critical speed using the scale model is considered to be feasible. Therefore, the numerical analysis and test results using the scale model to analyze the influence of wheel wear on the critical speed is sufficiently useful to analyze the critical speed of a full-scale vehicle.

8. Conclusion

To analyze the influence of the wheel profile wear on bogie stability, a study using a scale model was conducted. A dynamic model for full scale and 1/5 scale bogie model were constructed, and the critical speed for the worn wheel profiles was analyzed. The 1/5 scaled wheel, bogie and roller rig prototypes were designed and manufactured. Using these scale models, the critical speed tests were conducted on each worn wheel profile.

From the result of the critical speed analysis on scale bogie model, the influence of wheel profile wear on the critical speed shows a similar trend with the results of the critical speed for full scale model. It appears that the equivalent conicity is increasing with the increase of wheel flange wear, and the critical speed is inversely proportional to the equivalent conicity. The critical speed test results using the scale bogie prototype showed good results, and error between the simulation and test was less than 5%. Moreover, as seen in the variation of the critical speed for the wheel profile wear, the test results for the scale model were very close to the simulation results of the full scale model.

Therefore, it is concluded that the analysis and test result using a scale model in order to analyze the influence of critical speed for the wheel wear are sufficiently useful as a model to analyze the critical speed of a full scale bogie. But, this study was limited to a conical type wheel profile inclined 1/20. In the future, it is thought that studies on a 1/40 inclined conical-type wheel profile and a 1/20 inclined arc-type wheel profile, which was not done in this paper, should be continued.

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