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Preliminary Design and Development Framework of Railway Vehicle Simulator for Engineering Evaluation Analysis

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Abstract

The purpose of the present study is to develop conceptual design of a railway vehicle simulator based on a scaled model. Although the scaled simulator is limited in its ability to manipulate the full dynamics of a full-size railway vehicle, it has been known to have an advantage in that it could provide means of testing the fundamental dynamic behavior within a limited laboratory space and at low operation cost. The present study proposes a design strategy for a simulator so that a small scaled roller rig could be fabricated and operated in laboratory setting based on the design philosophy. The data obtained from experimental testing using a scale model can be used to verify and interpret the dynamic performance of full-scale railway vehicle by applying appropriate non-dimensional analysis.

Keywords **:** *Railway vehicle simulator, Scaled bogie, Similitude method*

1. Introduction

There are only few countries in the world that develop and manufacture complete railway vehicle system by themselves. After high-speed railway had been introduced in transportation market, making railway vehicle faster and lighter has become an important issues, along with operation safety and passenger riding comfort of railway vehicle. The issue of railway vehicle dynamic characteristics also is an important task since dynamic characteristics of railway vehicles should be examined of whenever a new railway vehicle is developed. Constructing a small scale railway-vehicle and using it for the simulation of real-vehicle operation can be an effective approach.

In this study, a model-based test method using scale-down railway vehicle and similarity theory will be used as an alternative to overcome the difficulties associated with the real-vehicle experiment. Model test is not as precise as full-scale-vehicle experiment. However, it can save substantial test cost and expense by doing the test in a small lab space. When there is no real-vehicle size model, a scaled model appropriate to the testing purpose can be constructed. In such case, the similarity principle is used so that the dynamic properties of scaled model are physically equivalent to the real-vehicle. In overseas railway-vehicle research centers, 1:3, 1:4, 1:5, 1:6, 1:n scaled model test equipments has been developed for test evaluation.

MMU Group at Manchester Metropolitan University in U.K., Railway vehicle Test Center of Europe INRETS, DB in Germany, SNCF in France, FRT in U.S., NRC in Canada, VRC in China and Torino University in Italy do such simulation of railway vehicle in laboratry.

These centers operate equipments for scaled model test together with real-vehicle model. The small simulation models they use are mostly 1:n scaled railway vehicles. According to the reports in previous studies, there are test items that can be realized dependent on models and design purposes. The operation results of small simulator for design specifications were found to be quite similar to the data from real-vehicle test. Therefore, if the required test items can be correctly defined during the design stage of test equipment, the test approach using small simulator can be a useful tool for predicting the dynamic characteristics of railway vehicles

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2. Outline of Railway Vehicle Simulator Development

2.1 Motivation for development

The purpose of this study is developing an instrument system that tests and measures the dynamic phenomena of railway vehicle directly related to the derailing accident of railway vehicle. The system consists of railway vehicle, design/manufacturing of driving device that simulates the railway-vehicle operation, installation of measuring device and the test data collection device.

The test should cover various physical phenomena occurring on the railway vehicle having the same physical specifications with a real-vehicle. However, the weight of real-vehicle is 30 to 40 tons and the length is more than 20 meters. It is a big and heavy structure. Though it would be most ideal test if a real-vehicle could be used; however, there are limitations in cost and physical dimension to test dynamic characteristic of real-vehicle. In other words, a large test space, a large scale test equipment that can drive heavy real-vehicle and high cost of testing are required for the real-vehicle test.

Small simulator using scaled model railway vehicle is a test method that can complement the realistic difficulties associated with full-scale real-vehicle test. The system developed by this study will reduce the size of real-vehicle on certain ratio and the ‘similarity imitation technique theory’ developed in engineering will be applied on the process that handles the measured signals during the test. Then the properties of physically scaled model will be calibrated.

2.2 Scaled model and the similarity theory

The early similarity theory was developed to deal with viscous fluid related issues of Reynolds. Today the similarity theory is applied to fluid dynamics, aerodynamics, chemical process dynamics and engineering practice including mechanical engineering design.

In the early stage, researchers used dimension calculation method that secured several dimensionless groups. Another method made a dynamic formula and classified the scale factors using common elements that maintain the similarity.

Choosing a material property value is one of the important elements and the loading condition also affects similarity. The U.K. railway uses aluminum wheel and roller, Matsushida of Japan uses steel material and other uses plastics. Each has its own approach and loading condition.

The scaled simulator model is the equipment developed for the realization of dynamic characteristic of real-vehicle on laboratory scale. Therefore, the model should have functions that consider the physical variation of real-vehicle while test should be done in comfortable and realistic way.

Scaled model is based on the similarity theory of Reynolds. The outline of similarity theory is that once the dynamic characteristic and material properties can be defined, the equivalent theory of physical phenomena can be established by the similarity theory.

The Railway vehicle Simulator is used for i) verification and evaluation of model, ii) basic study of dynamic characteristics phenomena during bogie development and iii) railway-vehicle dynamic simulation or demonstration.

2.3 The configuration of railway vehicle simulator

2.3.1 Roller

It was possible to get the basic knowledge on dynamic characteristic modeling between rail and wheel and test information from the scaled model which was first developed by DLR in Germany. The roller of early scaled model is made of tubes with 20 mm thickness. At the end of each tube, a disk, which is 1:5 scaled model of UIC 60 rail, is connected. The diameter of roller is 360 mm and each disk is placed with the length corresponding to 287 mm, which is the scaled model of rail gauge. This type of roller is very stiff toward bending; therefore, it works as an ideal rail. Meanwhile, the error impact of roller rotating speed can be avoided since the rotating inertia moment of roller is also big.

The distance between rollers is equivalent to the wheel axle of the model. Since the bogie wheel axle of real-vehicle varies in the range of 2,000 mm to 2,800 mm, the distance between rollers is designed to vary in the range of 400 mm and 560 mm. Schmidt-Coupling is used to maintain this varying distance.

The axle of the motor is connected to the belt which has defined stiffness in longitudinal direction. A belt with teeth to prevent slipping is used and the belt moves between minimum speed (0) to maximum speed (900 U/min~ 1100 U/min). This speed is equivalent of 140 km/h to 168 km/h.

2.3.2 The bogie model

Bogie is designed to analyze the dynamic characteristics of railway vehicle. It should be designed so that the mass and rotating inertia would meet the scaled ratio. When designing bogie, followings should be considered; i) a light-weight framework structure that connects the axle bearing and four material points, ii) material points should provide with tilting movement which can control the camber angle of axle, iii) the framework structure consisting of two wheels will be joined by homo-kinetic joint and iv) there will be some connecting condition between joints.

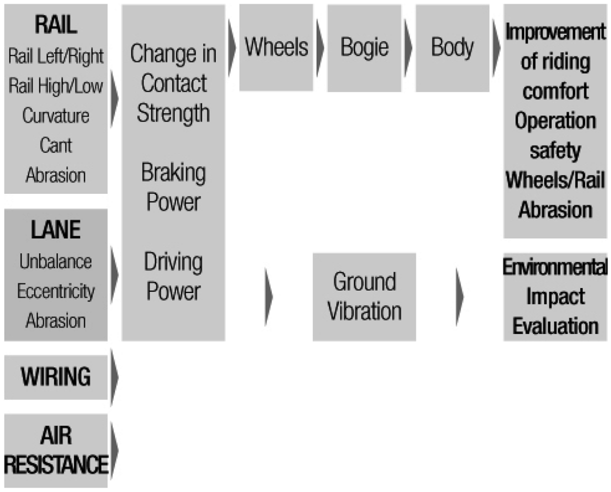

Fig. 1 Dynamic characteristic phenomena of railway vehicle

3. Case Studies on the Overseas Research

3.1 Small simulator at MMU (U.K.)

The railway technology study team at Manchester Metropolitan University (MMU) in U.K. led by Professor Simon Iwnicki is working on how to improve the locations in the suspension design of general railway vehicle. The small simulator of this team precisely realizes the tangent line force occurring at the exact contact point between the wheel and rail. This force has big impact on tangent line direction However, it has small impact on the movement applied to railway vehicle in vertical direction. Therefore, the driving part is designed to consider the yaw phenomenon and lateral movement of wheel-axle/rollers in order to easy interpretation of complex phenomena.

3.1.1 System configuration

System moves at the similarity-speed of 250 mph so that the suspension of high-speed railway vehicle suspension can be studied. Driving is achieved by moving pulley and belt connected to each roller shaft by electric motor and driving controller. The rollers in each position of wheel axle are joined by hook joint shift and spline for safe connection. In order to simulate the irregular operation out of track, the rollers move in lateral direction and rotate around the vertical axle line. These movements are supplied by servo hydraulic actuator and digital controller. They are controlled by defined waveform or certain data. The roller device (rig) has piezoelectric accelerator and movement sensor to measure the railway-vehicle movement. The strain-gauge type external force measuring sensor is attached to the end of the roller shaft so that it can measure the lateral force component applied on the wheel and rail.

3.1.2 Utilization of simulator

Roller device is generally used to evaluate the durability of wheel/rail, design of suspension and various movement of railway-vehicle occurring between independent wheels. It is also used for the evaluation of various active or semi-active suspension effects.

The defect or excess in cant will get impact from the slope of roller frame. This will be applied on the normal rotation at fixed varying curve; however, the dynamic tilting angle should be considered at the next stage so that the yaw phenomenon and dynamic curve test can be applied. At present, the important task is improving the system by reducing the effects caused by the original error of the roller rig coming from the different conditions between the scale, roller and movement on the rail. The studies on this subject are ongoing now.

3.2 The small simulator at DLG (Germany)

The development of the dynamic system at DLG, Germany, has been stimulated by the appearance of simulation software for railway-vehicle dynamic based on the 'super-multi-object modeling technology' in early 1970s. Especially, the railway vehicle wheels that have non-linear movement in wheel-rail were studied. The tests were forecasting and modeling of dynamic response occurring from the branch of system formula with periodical solution. Therefore, the roller device and scaled bogie model were examined for the design and measured by software application. The design of scaled bogie from the bogie of MAN had started in 1984 and the basic knowledge and elements in wheel-rail dynamics were obtained.

3.2.1 System configuration

The test framework consists of two rollers with 20 mm thickness tubes as the driving part. The end of the tube is connected to the disk. It is made as 1/5 scale side view of UIC 60 rail.

The distance between two rollers is same with distance between wheels of the model. This distance continuously varies between 400 mm~560 mm. It is applied of the actual scale bogie wheel which is 2000 mm~2800 mm. The variation of roller distance is provided by parallel crank mechanism, which is called the Schmidt-Coupling.

The roller is connected to the belt with longitudinal stiff condition and it is driven by disk motor of DC controller. The rotating speed of roller depends on the rolling resistance of the wheel model and it is between 900 U/min~1100 U/min (140 km/h~168 km/h of real-vehicle), that continuously varies from 0 to maximum.

3.2.2 Utilization of simulator

Study on the operation behavior of scaled wheel, study on the scaling of scale factors related to dynamic similarity and the innovative design of scaled wheel model by dynamic similarity on real size wheel are possible using the simulator. Such railway vehicles are made in light and flexible structure. The evaluation is being done by non-linear mathematical proving method. The design considers the scale value of masses and the inertia moment by the boundary condition. However, an additional mass, which varies the moment of inertia dependent on the change in mass, is considered for accurate control of inertia moment.

The design of scaled bogie has light frame structure made of wheel bearing at four joint positions supplied to tilt motion and meeting the wheel camber angle. Because of this, the camber angles in each structure are paired by homo-kinetic joints. Two different joints can be connected with each other.

3.3 Comparative analysis of overseas simulators

The specifications of small simulators in U.K. and Germany are given in Table 1.

4. Design of Small Railway Vehicle Simulator

4.1 Design concept based on similarity theory

A dynamic formula applied on the railway vehicle should be considered first in the modeling of vehicle dynamics.

Table 1 Comparison of Overseas Scaled Models

SCALING	MMU	DLR	REMARK
No. of rollers	2/4 Connected Facing each other	2 Set of Stiff to bending	
Roller Diameter	0.25 m	0.36 m	
Roller Distance	0.4 m - 0.6 m	0.4 m - 0.56 m	
Max.Velocity	400 km/h	250 km/h	Correspond to actual size
Active Steering	Possible	Uneven	Wheelset in closed loop
Wheel Driving	Possible	Uneven	
Contact Force Measurement	Possible	Possible	Creepage Con.
Unevenness of Track	Possible	Not possible	Comfortable
Real Vehicle	Possible	Not possible	
Gauge Change	Possible	Not possible	
Curved Part	Partial	Not possible	Dynamic, Static

Table 2 Relationship between Real-vehicle and Scaled Model

	Item	Real-vehicle	Scaled model
Physical Quantity	Movement, Velocity, Acceleration	1	1/5
	Time	1	1
	Frequency	1	1
Material Rate	Density	1	1
	Young Modulus	1	1
	Poisson Ratio	1	1
	Friction Coefficient	1	1

$$m\ddot{x} + c\dot{x} + kx = F$$

$$I\ddot{\theta} + c_{\theta}\dot{\theta} + k_{\theta}\theta = M$$

The design model by this study suggests that having the time unit (among similarity factors) as 1:1 model like the U.K. scaled model makes the analysis and treatment process most simple. Therefore, the objectives of dynamic formula such as the movement (the independent physical quantity), speed and the acceleration unit are all compiled as 1:5 similarity units. On the other hand, since the material properties are used same with time unit, the density and Young modulus are within the frame of 1 to 1.

Table 2 shows the relationship between the scaled model and real-vehicle expected in the model with scale of 1:5 for length and 1:1 for time. The actual applications on the real-vehicle using the scaled ratio suggested in this study and the scaled model ratio on actual vehicle dimension suggest that the length units should all meet 1:5 ratios. The process of physical units being shown as the masses and rotating inertia moment suggest that they are all scaled down at the same ratio. Therefore, the scaled simulator can be reduced to 310 kg from 34 ton of real-vehicle weight and it can be handled in the laboratory.

4.2 Technical specifications

4.2.1 Motor

A gear box is required for speed change if the power is big. However, since there is an issue of vibration, the use of gear needs careful consideration. If the power is small or medium, the motor speed can reach up to 1,750 rpm when using general electric power. Therefore, when the scale is 1:2 in diameter, 900 rpm is highest elevated speed. The actual speed at this maximum speed is 320 km/hr level.

4.2.2 Movement control mechanism

The rail of railway-vehicle simulator should be able to

Table 3 Relationship between Real-vehicle and Scaled Model

Driving axle Speed (rpm)	Model Speed (m/s)	Model Speed (km/hr)	Real-Vehicle Speed (km/hr)
300	6	21	100
500	10	36	180
700	14	50	250
1000	20	72	360

control ±2 mm, 10 Hz up-down movement and ±2 mm, 50 Hz left-right movement. Therefore, if the movement control uses hydraulic device, it is possible to get the required power; however, the noise and generated heat should be controlled. Two sensors for each channel are required to measure the movement of hydraulic device. It is possible to use LVDT sensor (movement change) or Load Cell. The movement of vertical, lateral and in rotating direction should be measured. The driving channel of hydraulic device is driven by lateral actuator and Yawing actuator. LVDT 3 sets are required as sensors. The acceleration yaw rate should be controlled for complementary measurement; however, vertical control of frame is not required.

5. Conceptual Design and Development of Railway Vehicle Simulator

5.1 Preliminary design concept

5.1.1 Conceptual diagram of rail and wheel

Fig. 2 is the conceptual diagram of rail and wheel. It is designed in accordance with the similarity principle at 1:5 scale. The test bed rail and the wheel of scaled railway-vehicle will be designed same as the cross section of actual bogie model wheel. The scaled bogie of railway vehicle is on the rail of the test bed and it will move in accordance with the movement of the rail. The specifications of the rail calculated by the similarity principle is; diameter 400 mm, width 287 mm and front/rear distance 500 mm. The wheel specifications are: diameter 200 mm, width 287 mm and front/rear wheel distance 500 mm.

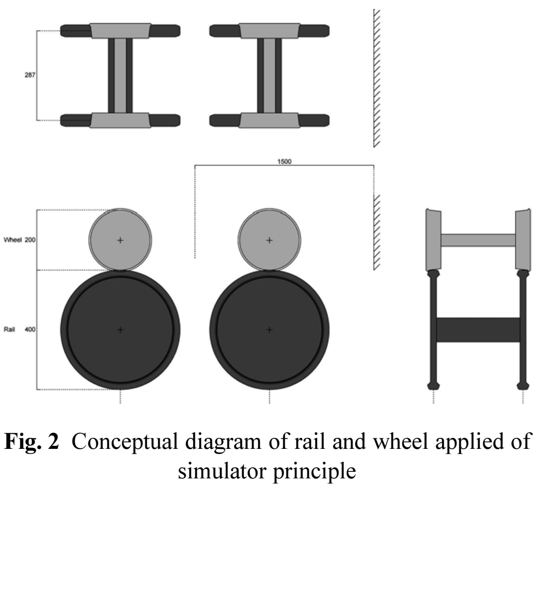

Fig. 2 Conceptual diagram of rail and wheel applied of simulator principle

5.1.2 Auxiliary structure of rail

Since real railway-vehicle has up-down and left-right movements simultaneously during operation, the design considered both up-down and left-right movements as in Fig. 3. The rail powered by a motor is connected with up-down movement auxiliary structure through bearing. Regarding the left-right movement auxiliary structure, it is connected with a spring supporting the up-down movement. The left-right movement auxiliary structure supported by spring has the same amount of movement in the left and right directions.

5.1.3 Scale-down bogie and test bed

Since real railway-vehicle has rotating movement along the rail during operation, the design enables the rotating movement of main structure during the rail operation as

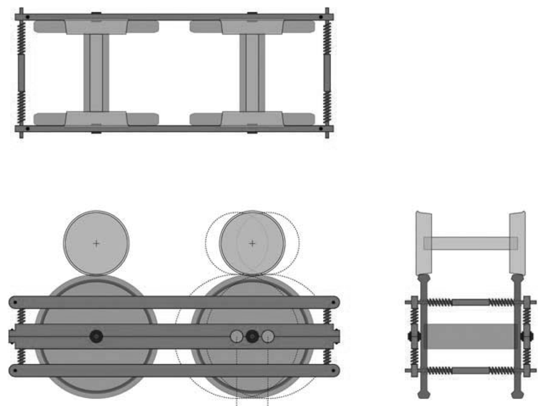

Fig. 3 Conceptual diagram of rail auxiliary structure

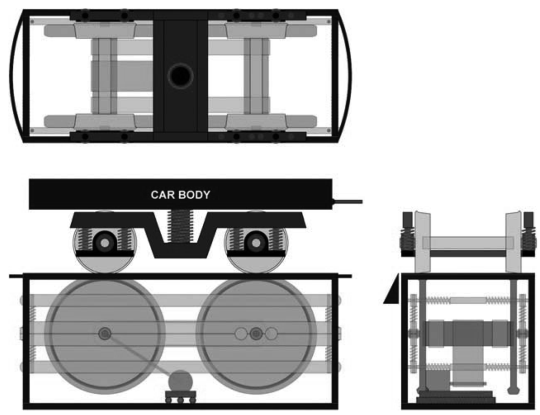

Fig. 4 Conceptual diagram of rail auxiliary structure

seen in Fig. 4. The test bed supporting the rail auxiliary structure can have rotating movement. The rotating movement is manually controlled by a handle and an index shows the movement.

5.2 Three-dimensional engineering design reflecting the preliminary conceptual diagram

Fig. 5 is the small simulator realization of the preliminary design concept and overseas cases. It can test wheel speed of 150~262 km/h when the scaled bogie weight of railway-vehicle is 200 kg. 10 kN Hydro Static Servo Actuator had been installed so that the lateral vibration 0.6 mm can be controlled at 10 Hz.

5.2.1 Cant controlling function

In order to analyze the curved rail operation of railway vehicle, the design has the Cant adjustment function considering the ±3° gradient of attack angle as seen in Fig. 6.

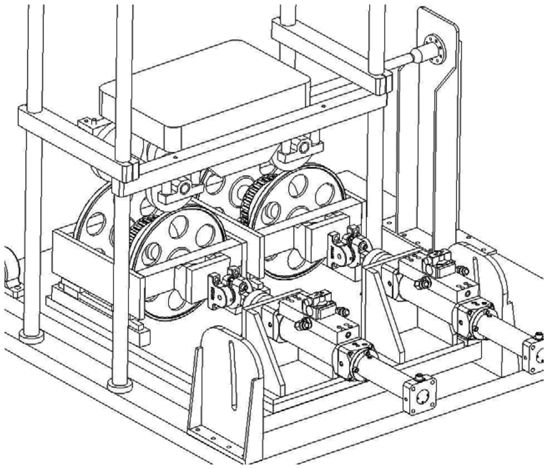

Fig. 5 Three-dimensional engineering design of small simulator

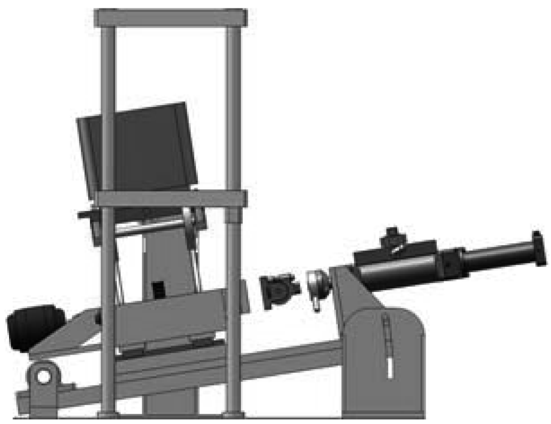

Fig. 6 Cant design

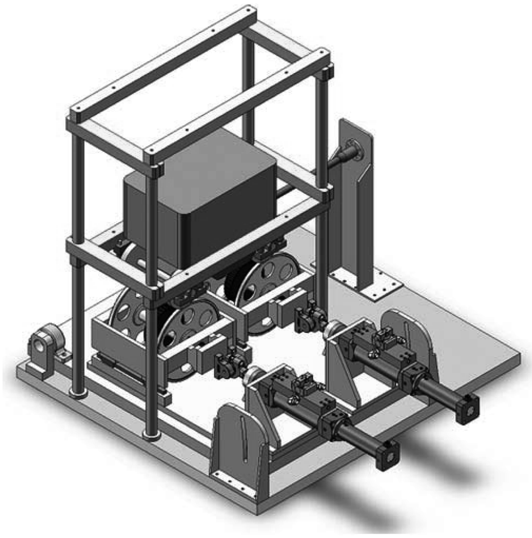

Fig. 7 Three-dimensional rendering image of small simulator

5.2.2 Operation safety of simulator

As seen in Fig. 7, the design has drive-motor stop function, hydraulic-actuator stop function, scaled bogie fixing wire and safety device when derailing and the safety frame(guard) for safety purpose.

6. Conclusion

Research using scaled model of railway vehicle is an effective method to save time and cost in the evaluation and prediction of vibration of railway vehicles. If a method, which can confirm the dynamic phenomena and predict the response of the structure by a test using scaled model, can be developed, compared and verified, it would represent a valid engineering means to get useful results on how the operation of real railway-vehicles would operate.

This study verified the actual dynamic response based on the test in laboratory using scaled railway-vehicle model. It can be useful in the design of the actual structure and securing the durability of parts.

This study suggested the engineering solution on the small railway vehicle dynamics by way of scaled model test and arrived at dimensionless dynamic formula. It is expected to contribute to the technology of local rail industry.

A signal handling method that can be applied to the small railway vehicle test has been also developed and suggested. It will contribute to the evaluation of railway vehicle stability and reliability. As the method can be applied to small railway-vehicle, test cost will be saved and the testing can be done anytime.

The results of this study suggest three possible utilization areas, which are: evaluation of railway vehicle operation stability, evaluation of passenger riding comfort of railway vehicle and understanding of the abrasion characteristics between rail and wheel.

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