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Simulation Technology for Railway Vehicle Dynamics

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Abstract

Railway vehicles must have high kinematic performance, which is evaluated in terms of running stability, curve negotiating ability, and ride quality, and to improve this performance, it is essential to adequately design the characteristics of the spring systems of bogies. In addition to tests on real vehicles, computer simulation is effective at enhancing the vehicle performance by adequately evaluating the characteristics of spring systems in the design stage. First, this study presents the characteristics of computer simulation for railway applications and related evaluation technologies, and then, as examples of simulation technology of the company, evaluation of the kinematic performance of the bogies for the linear-motor metro transport system, and estimation of the bending stress on wheel axles for vehicles for conventional lines.

1. Introduction

Railway vehicles are transport systems designed to run safely and smoothly on tracks separately provided. They are significantly different from automobiles and other transport systems in that they run on tracks comprising straight and curved portions and employ drive and brake facilities without depending on active steering means such as wheel steering systems or rudders. Here, railway vehicles must satisfy mutually conflicting requirements: rectilinear stability on straight-line tracks (running stability) and turning performance on curved tracks. In addition, it is important for them to maintain high ride quality or being invulnerable to vibrations when passing through irregular track portions or switching points. In other words, it is very important for railway vehicles to have good running stability and turning performance while providing good ride quality.

A railway vehicle is supported by bogies, which in turn are supported by wheelsets. The rigidity and damping properties of the spring systems provided at these points of support significantly affect the running performance of the vehicle, and therefore, it is necessary to adequately select the characteristics of the springs. Therefore, various methods for evaluating the performance of vehicles and their components have been proposed and put into actual practice, which include unit test on test beds, test run on in-plant tracks, and trial runs on commercially operated lines. In addition to these tests using real objects, computer simulation based on calculation technology has been used lately.

It is well known that simulation is highly instrumental in studying specifications at the design stage of railway vehicles from the concurrent engineering viewpoint, especially in selecting and evaluating design parameters, and it has been used in the field of railway engineering as widely as it is in other fields of industry.

The present study first explains the characteristics of simulation technology for railway engineering, and in Sections 3 and 4, the evaluation items related to the kinematic performance of vehicles, and then, it presents typical cases of the application of simulation to the design of vehicle components.

2. Characteristics of Simulation Technology and Items of Evaluation

2.1 Characteristics of simulation technology for railway vehicles

Typical construction of a railway vehicle is given in **Fig. 1**. A railway vehicle consists of wheelsets, bogies, and a body; the wheelsets and the bogies are connected together through primary suspension systems and the bogies and the body through secondary suspension systems. The characteristics of these suspension systems have significant effects on the kinematic performance of the vehicle.

As in the case of common motion dynamic analysis, to analyze the kinematic performance of a railway vehicle, each of the components given in Fig. 1 is expressed as a rigid body, and equations of motions in the vertical, lateral, and longitudinal directions are formulated in consideration of the spring rigidity and damping properties of the suspension systems. Then, according to track and running conditions separately given, the kinematic behavior of a railway vehicle

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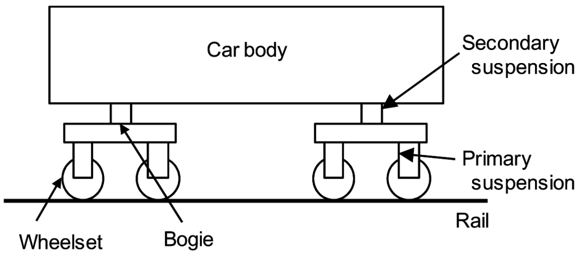

Fig. 1 Configuration of railway vehicle

is analyzed through simulation based on multibody dynamics.[1,2)]

As track conditions, the following things are typically taken into consideration. First, at a curve, the track is slanted toward the inside to cancel out the centrifugal force on the vehicle; the superelevation of the outer rail relative to the inner is called a cant. There is a twisted track portion called a transition curve between a curve with a cant and a straight portion without it. In addition, the distance between the rails is larger in curves than the prescribed rail gauge so that bogies can go over the curve easily; this gauge widening is sometimes called a slack.

Furthermore, the model used for simulation must take different factors into consideration in accordance with the object; when the object is being evaluated for the ride quality of a vehicle, the simulation model will have to include factors such as the elasticity of the body and the track, and the vertical and lateral misalignment of the track.

The most notable characteristic of the kinematic simulation of railway vehicles is the fact that the force between the wheels and rails plays a significant role. The diagram in **Fig. 2** shows the behavior of a bogie and the longitudinal and lateral forces between the wheels and the rails at a curve, and **Fig. 3** illustrates the contact forces in the vertical and lateral directions between the wheel and the rail on the outer side of a curve. The creep force in the diagrams is the frictional force between the contacting surfaces of the wheel and the rail when the former rolls on the latter.

The creep force is formulated using the shape of the contacting surfaces of the two elastic bodies, microslip resulting from the rolling motion, and the elasticity moduli of the two bodies. The creep force in the railway dynamics has following characteristics: first, because the wheels on both sides are fixed onto a common axle, they are restricted by each other in terms of dynamic behavior and slip is likely to occur with either of them; second, the modulus of elasticity applicable to railway wheels and rails is far higher than that applicable to automobile tires and road surfaces. Because of these characteristics, creep force has significant effects on the analysis of the kinematic performance of railway vehicles.

The research into determination of the creep force acting between a railway wheel and rail began in the 1920s, and the method of calculating it was established by Kalker, a Dutch researcher, sometime around 1990.[3,4)] Today, while some formulae for calculating the creep force are available in the market as software packages, various points still remain unclear about how to obtain it when a wheel contacts a rail at two points or more, and efforts are being made to clarify such problems.[2,5)]

Different analytical methods are employed for evaluating different aspects of the kinematic performance of a railway vehicle: transient dynamic analysis is used for running simulation, frequency response analysis for evaluating vehicle behavior under a condition having specific frequency characteristics, eigenvalue analysis for

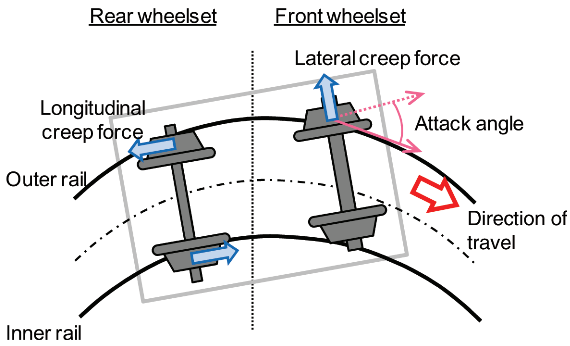

Fig. 2 Bogie behavior during curve negotiation and contact force between wheel and rail

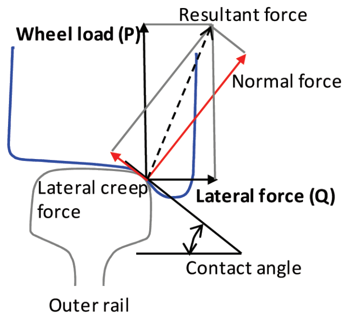

Fig. 3 Contact force between wheel and rail on vertical section

evaluating the mode of nonstable vibration, etc.

In the early days of simulation of railway vehicle dynamics, vehicle builders exclusively prepared calculation programs for their own use; however, in the 1990s and thereafter, various calculation programs for multibody dynamics were developed by railway technology institutes of different countries, and some of them have been made commercially available as generic tools;[6)] such tools are widely used now. Nippon Steel & Sumitomo Metal Corporation uses in-house programs and outside tools as suitable for different simulation objects. Sections 2 and 3 of this study present examples of evaluation of vehicle dynamics on the basis of transient dynamic analysis by using a general-purpose simulation tool SIMPACK™.

2.2 Items of evaluation

As shown in Fig. 3, wheel load (P) and lateral force (Q) act between a wheel and a rail; their magnitudes are determined by the contact force between the two bodies. To confirm running safety and dynamic performance of a bogie or to obtain the reference parameters for track maintenance, these values are often actually measured. This is usually done by attaching strain gauges to wheel discs of a test vehicle and then having the vehicle run on real tracks or by attaching strain gauges to rail webs and then having ordinary vehicles run on the rails. **Photo 1** shows a wheelset used for the former case. This type of wheelset is called a PQ wheelset; strain gauges are attached to the holes in the disc of each wheel, and the wheel load and the lateral force are obtained from the strain measured with them. Results obtained by this method are explained in the following section.

Simulation results are utilized in case studies typically in the following manner: the accuracy of calculation results is verified against the results of actual measurement of wheel load and lateral force. Bogie behavior and creep force, which are difficult to actually meas-

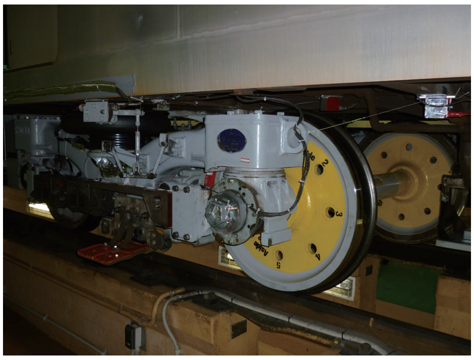

Photo 1 Bogie for wheel/rail contact force measurement

Photo 2 Rotating-disc type test bed for bogie

ure, are estimated through calculation, and then on the basis of the evaluation of dynamic performance of the vehicle in question, its design parameters are adequately modified. In consideration of such use of simulation results, wheel load and lateral force were evaluated in the examples described in the following sections.

To supplement the above explanation, **Photo 2** shows the bogie test bed at Nippon Steel & Sumitomo Metal's Osaka Steel Works. Here, in place of a rail, rotating steel disc is provided for each of the wheels, and the running stability, ride quality, etc. of a bogie are evaluated by turning the wheels at speeds corresponding to real operation. The facility, which is called the rotating-disc test bed on account of its configuration, has proved highly instrumental in bogie design.

3. Evaluation of Bogies for Linear-motor Metro System

3.1 Background

"Linear-motor metro" is the name given to the linear-motor traction subway system wherein the sectional area of the tunnels can be made smaller than those of conventional ones. It was developed under the auspices of the Japan Subway Association, and the first subway line under the concept, the Nagahori–Tsurumi Ryokuchi Line of Osaka Municipal Transportation Bureau, began its commercial operation on March 20, 1990. By using the linear-motor traction, the sectional area of tunnels can be made smaller and the line plan can be made to have a greater freedom from restrictions, and consequently, the construction costs can be lowered. Thanks to these advantages, the system is now regarded as a potent means of transport for urban centers: the Oh-edo Line (Tokyo), the Kaigan Line (Kobe), the Nanakuma Line (Fukuoka), the Imasato-suji Line (Osaka), and the Green Line (Yokohama) have been constructed according to this

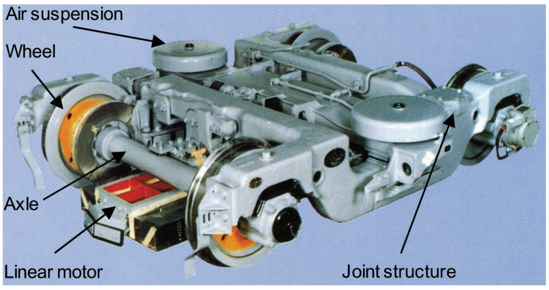

Photo 3 Bogie for linear-motor metro

concept by respective municipalities, and another line will be shortly inaugurated by the Sendai Municipal Transportation Bureau. This section reports how computer simulation was applied to the evaluation of wheel load and lateral force of the bogies for the system.

3.2 Characteristics of bogie [7-9]

Nippon Steel & Sumitomo Metal manufactured and supplied all the bogies for the cars of the linear-motor metro lines now in operation in Japan; **Photo 3** shows an example. This type of bogie is characterized by a linear motor unit provided under the frame of a jointed structure and wheels smaller in diameter than those of conventional subway trucks, making it possible to lower the body floor level; the use of linear motors enables low-floor and compact car design.

The enquiry specifications for the trucks included various points that required special measures. First, because the trains are driven by the attraction and repulsion between the linear motor units provided under the truck frame and the reaction plate along the track center, the gap between them must be kept as constant as possible. For this purpose, the wheel suspension was designed more rigid, especially in the vertical direction. On the other hand, subway lines have many tight curves, and good curve negotiating ability is important For this purpose, good balance between longitudinal and vertical rigidity of the wheel suspension is important for meeting the requirement. In addition, the jointed frame with relaxed torsional rigidity serves to improve curve negotiating performance.

3.3 Evaluation of wheel load and lateral force

A calculation model for simulating a test vehicle was formulated; track and running conditions were input to the model in accordance with those of the tests on real lines; and the accuracy of the simulation was verified by comparing the calculated wheel load and lateral force with those actually measured during test runs using real vehicles.

The schematic illustration in **Fig. 4** shows the outlines of the calculation model simulating the bogie for the linear-motor metro; all the structural members, links, springs, and dampers composing the object bogie were incorporated in the model. The main specifications of the bogie were as follows: wheel base, 1,900 mm; wheel diameter, 650 mm; rail gauge, 1,435 mm; maximum width, approximately 2,500 mm; and distance between two bogie centers 11,000 mm.

Test runs were conducted, as shown in **Photo 4**, on the test line in the premises of Nippon Steel & Sumitomo Metal's Osaka Steel Works. The test line consists of a straight portion (tangent), a transition curve (spiral), an arc portion (constant curve) 100 m in radius, another transition curve, and a second straight portion. The change in the vehicle speed during the test is given in **Fig. 5**; the vehicle speed change was also fed to the computer as a simulation condition.

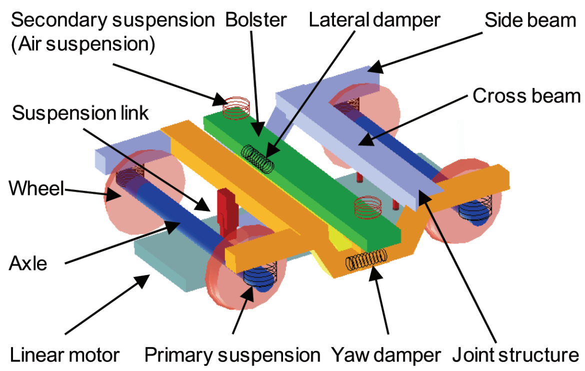

Fig. 4 Simulation model for linear-motor metro bogie

Photo 4 Test line at Osaka Steel Works

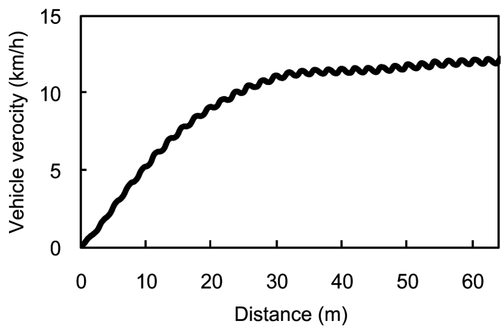

Fig. 5 Vehicle velocity at field test

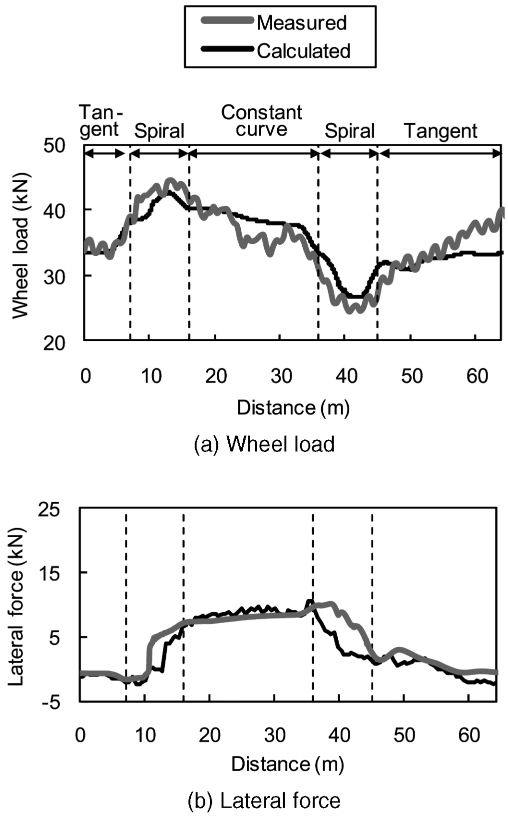

Fig. 6 Comparison of wheel load and lateral force on outer rail

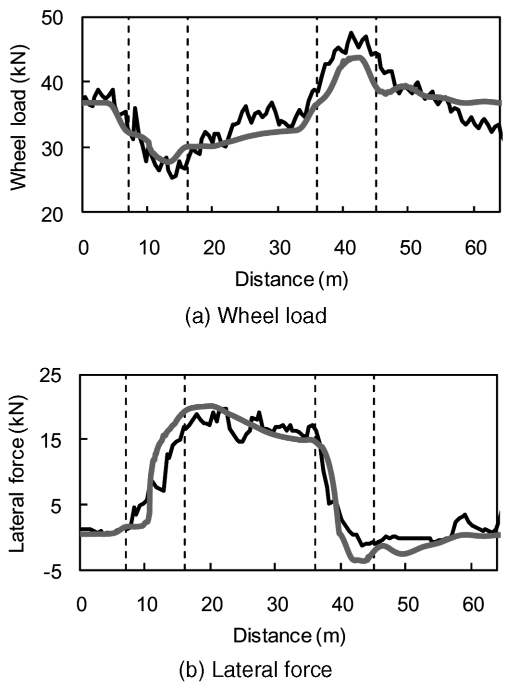

Fig. 7 Comparison of wheel load and lateral force on inner rail

The simulated and the measured wheel load and lateral force of the outer wheel of the leading axle of the test vehicle are compared in **Fig. 6**, and the same of the inner wheel in **Fig. 7**; the track conditions designated between the above parentheses are given above the top-most graph.

These graphs demonstrate a good agreement between the simulated and the actually measured values. The authors thus confirmed the effectiveness of the simulation at accurately evaluating the wheel load and the lateral force as well as the relationship of these values on the outer and inner sides and their chronological changes. The simulation based on the models explained above has been used for evaluating the kinematic performance of the linear-motor metro bogies after they were commissioned too.

4. Evaluation of Stress on Wheel Axle [10-12]

4.1 Background

Axles for railway vehicles are designed according to the provisions of the Japanese Industrial Standards.[10] While the value of the maximum bending stress for the axles is defined on the basis of the vehicle weight, maximum operating speed, dynamic load, etc., development of a method for evaluating the axle stress under changing running conditions, such as curves of different radii at different train speeds, has been awaited. In view of this situation, the authors studied the possibility of estimating the axle stress under different running conditions by simulation.

This section reports evaluation of stress on wheel axles for conventional, ordinary-speed lines using simulation models taking changing running conditions into account and comparison of the simulation results with those of tests on a real vehicle.

4.2 Running test with real vehicle

4.2.1 Test conditions

The specifications of the test vehicle are as follows: wheel base, 2,100 mm; wheel diameter, 860 mm; distance between bogies, 13,800 mm; weight, 41,800 kg; and rail gauge, 1,067 mm. The track and driving conditions for the test are given in **Table 1**: the curve radii ranged from 600 to 1,400 m, and the train speed was approximately 100 km/h.

4.2.2 Method of measuring stress on wheel axle and measurement results

The object wheelset and the stress measurement point are shown in **Fig. 8**. The wheelset was supposed to be used as the first wheelset of the leading vehicle of a train, and in addition to stress, wheel load and lateral force were measured at the same time. To avoid the position of stress concentration due to shape change, a strain gauge was attached at 80 mm to the center from the inside edge on the wheel on the second side; here, "the second side" means the left-hand side in the direction of travel, and therefore, the strain gauge will be on the inner side at a curve to the left in Table 1, and on the outer side at a curve to the right.

The graph in **Fig. 9** is an example of measured axle bending stress in a constant curve 1,200 m in radius (R-1200). As seen here, the bending stress on the axle changes sinusoidally following the wheel rotation. In view of this, the authors estimated the positive and negative peak values by simulation.

Table 1 Track and driving conditions

Track conditions			Driving conditions
Curve radius (m)	Cant (mm)	Curve direction	Velocity (km/h)
600	101	Left	92
800	85	Left	101
1 000	84	Right	105
1 200	39	Left	102
1 400	43	Right	114

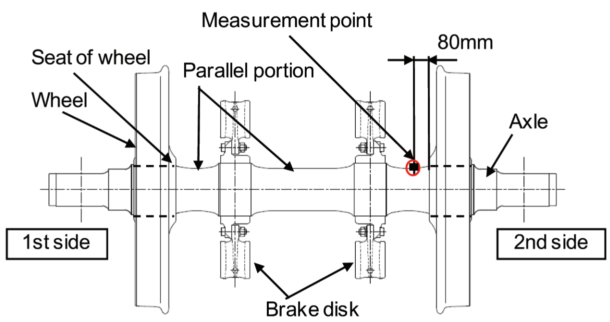

Fig. 8 Wheelset and stress measurement point

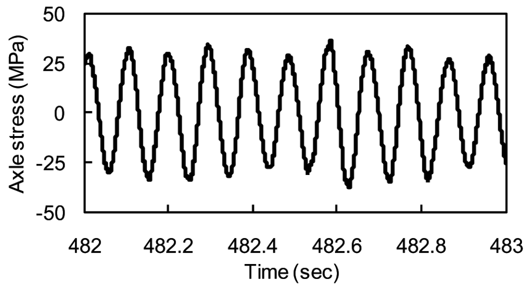

Fig. 9 Example of measured axle bending stress

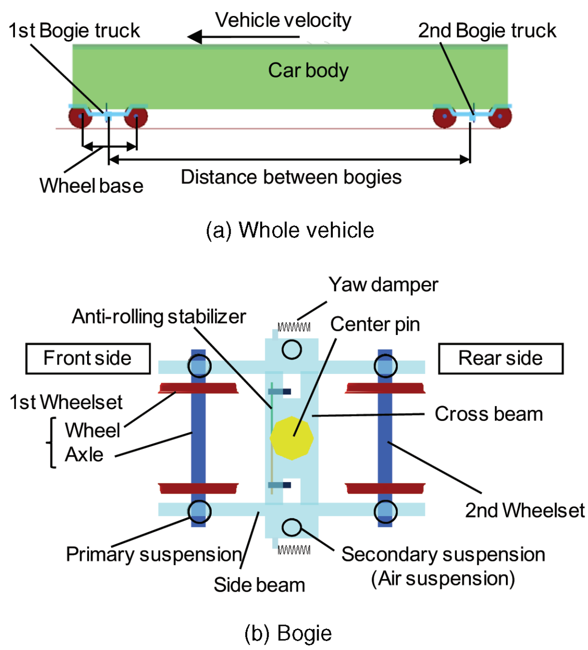

Fig. 10 Outlines of the simulation model

4.3 Simulation model

The simulation models of a vehicle and bogie are schematically illustrated in **Fig. 10**. The vehicle model consists of a body and two bogies simulating the true vehicle used for the tests on real tracks. The body and all the bogie structural members were regarded as rigid-body elements, the axle springs (primary suspensions) and the yaw dampers as linear-spring elements, the anti-rolling stabilizer as a combination of rigid-body and linear-spring elements, and the air suspensions as linear-spring elements.

SIMPACK ™, a general-purpose simulation program, was used. Note that the creep force acting between the wheels and rails was calculated using the FASTSIM algorithm [4] based on Kalker's simplified nonlinear theory, which was incorporated in the program as a calculation function. Here, a wheel was supposed to contact the rail at one point.

4.4 Simulation result

4.4.1 Evaluation of wheel load and lateral force

The graphs in **Fig. 11** compare the calculated and measured wheel load and lateral force at the R-1200 curve. Different from the calculation results, the values measured on the real vehicle fluctuated over time. This is presumably because of misalignment and small unevenness of the track, which were not taken into consideration in

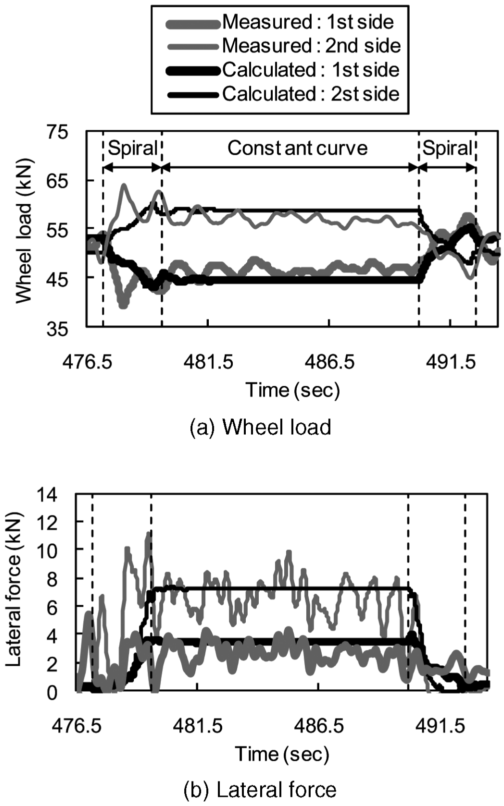

Fig. 11 Comparison of wheel load and lateral force

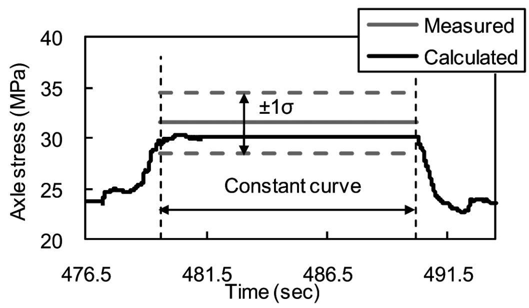

Fig. 12 Transient dynamic analysis of axle stress

the calculation. Taking this into account, the calculation results agreed considerably well with the measurement results.

4.4.2 Evaluation result

First, wheel load, lateral force, and bearing load were calculated using transient dynamic analysis on the basis of the simulation models, and then, regarding these as external forces on the axle, the bending stress on the axle was obtained using an equation of force equilibrium.

As an example, **Fig. 12** compares the calculated bending stress on the wheel axle at an R-1200 curve with that actually measured. Here, the object of the evaluation is to see if the simulated axle stress at the constant curve reflects the same actually measured. One can see from the graph that the calculated axle stress at an R-1200 curve is somewhat lower than the average of the measured stress; however, it is well within ±1 σ (standard deviation) of the measured value, which evidences that the calculation result was in good agreement with the actual measurement.

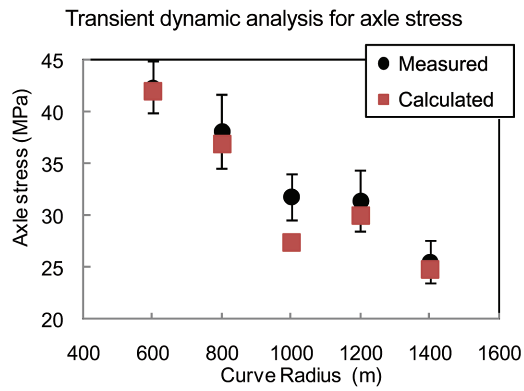

Fig. 13 Comparison of measured and calculated stress

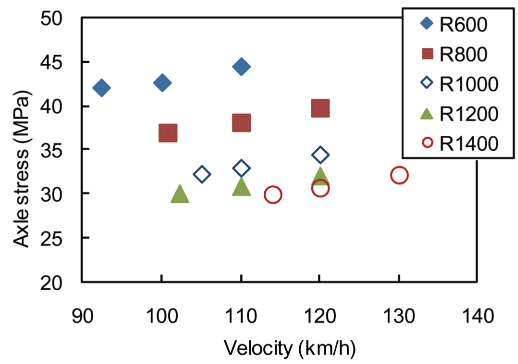

Fig. 14 Relationship between vehicle velocity and axle stress

In addition, **Fig. 13** compares the calculated and the measured axle stress at the curves listed in Table 1. Similar to Fig. 12, the average values and the ranges of ±1 σ of the measured values are given in the graph. The simulation agreed well with the measurement except for the case of R 1,000 m. This disagreement is presumable because the condition of the real test track was considerably different from what was assumed in the simulation; the causes of the difference are now being studied.

4.4.3 Case study (example)

As an example of case studies to which simulation models are applied, **Fig. 14** shows estimated axle stress in the curves listed in Table 1 at higher velocities. Here the estimation was done on the outer rail side.

The estimation indicates that the axle stress substantially increases in a linear manner with increasing vehicle speed. This indicates that it is possible by simulation to estimate the behavior of vehicle components under conditions not yet tested on real vehicles.

5. Closing

The present study has initially explained the characteristics of the simulation of the dynamic behavior of railway vehicles and typical indicators that can be evaluated using simulation, and then, described an example of the evaluation by simulation of the kinematic performance of bogies for linear-motor subway lines, and another of evaluation of the bending stress on wheel axles for conventional, ordinary-speed, 1,067-mm-gauge vehicles. Simulation technology is also effectively utilized in the fields such as wheel wear prediction,[13] monitoring of vehicle conditions during daily operation,[14] accuracy enhancement of air suspension models,[15] examination of curve negotiating performance in consideration of the shapes of wheels and rails after wear;[16] however, because of limited space, this study failed to cover these cases. Research and development are eagerly in progress in these fields.

Through effective use of general-purpose software tools, simulation technology makes it possible to obtain useful information that tests on real vehicles cannot reveal. On the other hand, if it is used on the basis of insufficient knowledge about the dynamics of vehicles, track constructions, and the nature of evaluation objects, the results can be misleading. It is therefore essential in employing simulation in R&D studies to verify the validity of simulation results against those of actual tests.

The authors intend to further promote fruitful combination of simulation technology with tests on real vehicles to develop excellent products and thus contribute to the advance of railway industry.

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