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KAWASAKI TECHNICAL REVIEW

Special Issue on Rolling Stock Engineering





Kawasaki Heavy Industries, Ltd.

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to an Exciting
World of Dreams
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Yoshinori Kanehana
President †

Please tell us the global environment surrounding the railway vehicle business and its business development going forward.

Railway systems are an earth-conscious, effective means of mass transportation. They are now under construction and are being extended in many areas of many developed countries, emerging countries, and developing countries. National projects of high-speed railways, cargo railways, and other types of railways are taking shape throughout the world. We are also implementing actions to win bids in collaboration with the government and private sectors on the basis of the success with the Taiwan Shinkansen.

However, the competitive environment of this business has become increasingly fierce: in addition to the European "Big Three," China Railway Rolling Stock Corporation has emerged as a huge company as a result of a business merger between CSR Corporation Limited and China CNR Corporation Limited, and the overseas production bases of Japanese railway vehicle manufacturers have started their operation and their low-price strategies.

To show the predominant presence of Kawasaki's railway vehicles in the world market to establish its status as the most reliable railway vehicle system

† At the time of writing
Senior Vice President
President, Rolling Stock Company

manufacturer for our clients in this business environment, it is essential to pursue unique technologies to develop technologies different from those provided by other companies. As a general heavy industry manufacturer, we possess a wide variety of state-of-the-art technologies. Our biggest advantage is that we can combine those technologies in the technical development of railway vehicles.

Please tell us which of your products are distinctive.

For example, we have commercialized a new-generation bogie, efWING, in which we were the first company in the world to use a CFRP frame with a suspension function. It is a uniquely differentiated product developed by combining technologies from our Aerospace Company, Corporate Technology Division Head Office, and other sections. We are the only company with such a product.

efWING is manufactured by using carbon fiber, an advanced material used for aircraft. This material was used for railway bogies for the first time ever. Thereby achieving significant weight reduction, and the decrease of wheel load has been reduced to less than half that of conventional products. As a result, efWING delivers excellent performance in "running safety."

To emphasize Kawasaki's character, we also placed importance on its design from the initial stage of its development. Based on affective engineering, we adopted a design created by total coordination of performance and appearance. Its impressive coloring and sophisticated functional beauty are changing the conventional image of railway bogies. In fiscal 2013, the design won the Good Design Gold Award for the first time as a bogie design.

This bogie has been well-received by our clients. In March 2014, Kumamoto Electric Railway Co., Ltd. started using it in the service operation for the first time in Japan. In 2015, running tests were performed by replacing service vehicle bogies with efWING in Shikoku Railway Company in March, Kyushu Railway Company in April, and Nishi-Nippon Railroad Co., Ltd. in October. Based on the performance results obtained from those tests, we are aiming to expand efWING sales in the Japanese domestic market and the world market.

What business area will you focus on going forward?

Rolling Stock Company has been focusing on the new-vehicle manufacturing business. However, the 2016 medium-term management plan has adopted enhancing stock-type business, focusing particularly on business based on IoT (Internet of Things).

For example, the vehicle maintenance work carried out by railway operators is required to change from maintenance according to time periods (Time Base Maintenance) to maintenance by monitoring condition (Condition Base Maintenance) in order to reduce lifecycle costs. Compared with other railway components, a bogie requires many inspections and many replacement parts, requiring much time to maintain. Since we possess many bogie-related technologies, we can provide a maintenance system that contributes to not only optimizing maintenance, but also to reducing the entire lifecycle cost of our clients by using our condition monitoring and diagnostic technologies based on IoT (bogie condition monitoring technology, track monitoring technology, etc.).

Closing comments

Rolling Stock Company's mission is that "we contribute to society by providing railway vehicles and other products that ensure safe, secure, and comfortable travel for users." Based on our advanced technical capabilities and quality, which are our core competencies, we will develop unique technologies different from those of our competitors, thus spreading the use of Kawasaki-brand railway vehicles in the world market.

Rolling Stock Market Environment and Initiatives of the Rolling Stock Company

Makoto Ogawara
Senior Vice President
President, Rolling Stock Company †

Introduction

Rolling Stock Company ("the Company") aims to contribute to society by providing people with vehicle products that support safe, secure, and comfortable travel as part of its vision to "become the industry's most trusted manufacturer of vehicle systems and provide dreams and excitement to customers worldwide through its outstanding teamwork and the highest level of technology and quality." The following describes the vehicle market environment in which the Company operates, its business development history, and its initiatives for the future.

1 Rolling stock market environment

Although the Japanese economy has been experiencing a modest recovery thanks to government-led economic measures, the falling number of passengers associated with the country's aging society and declining birth rate means that significant market growth cannot be expected. In recent years, demand has mainly been driven by the replacement of aging railcards, and since the total number of car orders has been on the decrease, railcar manufacturers continue to face fierce competition for orders.

At the same time, however, railcards have won recognition in countries and regions around the world for offering a more environmentally friendly means of mass transportation as they generate less CO_2 emissions than other transportation methods, such as automobiles and airplanes. In the United State and emerging countries such as India, Brazil, and Southeast Asian countries, many projects for the construction of high-speed railways and the expansion of urban transportation are planned for the purpose of stimulating the economy and generating employment. According to the Association of the European Rail Industry (UNIFE), the world rail market will grow at an annual average rate of 2.7% (NAFTA: 3.6%; Asia Pacific: 4.1%) until 2019, and continued market growth is expected.

The Company has been actively expanding its business overseas mainly in two markets: North America and Asia. In North America, in response to a growing population and as part of economic and employment measures, investment in social infrastructure is being proactively examined and demand for the addition and replacement of railcars has been generated for the Northeast Corridor, which is centered on New York. In Asia, against a backdrop of growing urbanization in emerging countries, investment in railway infrastructure has increased and there is strong demand for railcars in India and Southeast Asian countries. In addition, the Japanese government is taking a positive stance toward infrastructure exports as a priority for its growth strategy, including the provision of yen loans. Despite the strong overseas demand described above, we face fierce competition just like we do in Japan, as our competitors—the big three European manufacturers (Alstom, Bombardier, Siemens) and China Railway Rolling Stock Corporation (a Chinese state-owned manufacturer)—have a larger business scale than us.

2 Business development

In light of the above circumstances, the Company aims to achieve balanced, sustainable growth mainly in the three markets of Japan, North America, and Asia, with the world's highest technology and quality as its advantages. The following section describes the Company's business development and future initiatives, both in the Japanese and overseas markets.

(1) Development of the vehicle business in Japan

The Japanese market is the Company's most important market in terms of employment and regional economic promotion, as well as the enhancement of its mother factory functions in developing new technologies and products.

Having consistently remained at the forefront of cutting-edge technologies as Japan's top vehicle

† At the time of writing
Executive Officer
Vice President, Rolling Stock Company

manufacturer since it began operations at the Hyogo Works in 1906, the Company has served as a driving force for railway development and modernization and provided society with a variety of vehicles, including electric trains, coaches, freight cars, electric locomotives, and diesel locomotives, as well as related systems and equipment and new transit systems. On the technology front, we have stayed ahead of our competitors in developing state-of-the-art vehicles, such as Shinkansen trains, all aluminum-alloy trains, guide-rail system electric cars with rubber tires, completely automated new transit systems, and low-floor, battery-powered light rail vehicles (LRVs). In addition to the above, with customer requirements for countermeasures to deal with issues such as noise and vibration having become increasingly sophisticated and diversified due to the speeding-up of vehicles, we have responded by gaining support from the Aerospace Company, the Corporate Technology Division, and other divisions. In recent years, the results of our efforts have come to fruition in the form of Shinkansen trains, such as the Hokuriku Shinkansen E7 Series/W7 Series (Fig. 1), and limited express trains and suburban commuter trains for conventional railway lines, such as the 8600 Series limited express trains for the Shikoku Railway Company.

(2) Future initiatives in Japan

In the Japanese market, where order competition has recently become increasingly fierce, the Company will enhance its leading-edge technologies by taking full advantage of its outstanding quality and integrated management to differentiate itself from its competitors. Specifically, we will further develop not only leading-edge technologies that take advantage of synergies across our company segments, including the Aerospace Company and the Corporate Technology Division (efWING: environmentally friendly Weight-Saving Innovative New Generation Truck, high-speed railcars, etc.), but also standard commuter cars that meet the need for cost reductions and short delivery lead times (efACE: environmentally friendly Advanced Commuter & Express train).

In addition to the above, while maintaining high productivity in our high-mix, low-volume production, we are working on improving the Hyogo Works in order to respond to small- and medium-lot orders for vehicles with a complicated, highly sophisticated structure, such as limited express trains and event trains that offer originality, which have been increasing in number in recent years. We are also actively developing peripheral equipment for vehicles—including the bogie instability detection system and the track irregularity inspection system—to provide customers with value throughout the entire vehicle lifecycle. Furthermore, we are actively approaching new customers with the aim of providing our products to a broader range of customers. In FY2015, we received orders for new commuter trains from Seibu Railway Co., Ltd. for the first time, and orders for new limited express trains from Tobu Railway Co., Ltd. for the first time since 1946. In addition to existing customers, we will actively propose our products to new customers by making use of our high quality, state-of-the-art technological capabilities.

Fig. 1 Hokuriku Shinkansen E7 Series/W7 Series

(3) Development of the vehicle business overseas

The Company began exporting railcars in 1911 when Kawasaki Dockyard delivered four coaches to Qing, and we have delivered large numbers of railcars overseas ever since. The high quality, leading-edge technologies that the Company has nurtured in domestic projects have been well received, and more than half of the Company's consolidated net sales are now from overseas, mainly Asia and North America

In Asia, we have a proven sales track record, particularly in Singapore, Taiwan, and China. In Singapore, we received orders for urban transportation vehicle from the country's Land Transport Authority (LTA) for the first time in 1984, and have been providing railcars, including C151A subway cars (Fig. 2), for over 30 years. We now have the largest market share there with 64% of the market. In Taiwan, we have received orders for 34 high-speed trains (408 cars in total) from Taiwan High Speed Rail since 2000. In the field of mass rapid transit (MRT), we have delivered large numbers of railcars, such as the EMU for the Taiwan Taoyuan International Airport Access MRT System, since our first delivery of railcars to the City of Taipei in 1992. In China, we entered into a plant partnership with CSR Qingdao Sifang Co., Ltd. ("Sifang"), which is now a subsidiary of China Railway Rolling Stock Corporation but was under the umbrella of China's Ministry of Railways in 1985, and have built up a 30-year relationship of trust through our support for the planning of the company's vehicle plants, technical cooperation, and production cooperation.

In North America, following our export of tram cars for use by the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia in 1980, we have delivered double-decker train coaches for the Long Island Rail Road, PA-5 cars for the Port Authority Trans-Hudson Corp. (PATH), and various other types of railcars for over 35 years. The total number of cars ordered amounts to approximately 4,500. In particular, for the New York City Transit Authority (NYCT), we have delivered more than 2,000 cars in total since our first delivery of subway cars in 1985, thereby gaining the leading market share there. In 1985, we established the current Kawasaki Rail Car, Inc. (KRC) (Fig. 3) as an affiliated company in North America, and launched operations at our Yonkers plant the following year. We also established a vehicle plant for Kawasaki Motors Manufacturing Corp., USA (KMM) (Fig. 4) in Lincoln, Nebraska, in 2002 to enhance our production system. The KMM vehicle plant has successfully introduced an integrated manufacturing process that covers all stages from body structure manufacturing to final assembly. By improving our productivity, reducing our transportation costs, and mitigating our foreign exchange risk through local production, we have satisfied the "Buy American" provision that requires companies to procure at least 60% of US-made parts. The Company, as a locally based vehicle manufacturer, is further striving to provide

Fig. 2 C151A subway cars for Singapore's Land Transport Authority

Fig. 3 Kawasaki Rail Car, Inc. (KRC)

Fig. 4 Kawasaki Motors Manufacturing Corp., USA (KMM)

low-cost, high-quality vehicles and improve customer satisfaction by responding quickly to problems and providing other services.

(4) Future challenges in overseas markets

In the same way as we do in the Japanese market, we aim to build up a relationship of trust with our overseas customers by taking full advantage of the overwhelmingly high-quality technological capabilities we have achieved through our integrated management and contract fulfillment capabilities, including the meeting of delivery times, and to continue winning orders by strengthening our non-price competitiveness without falling into a price competition with Chinese and Korean manufacturers.

To strengthen our competitiveness, we will first of all form flexible partnerships to implement projects with an optimal scheme. Having formed a consortium with Sifang, we are currently working on the MRT train project for Singapore's Land Transport Authority (LTA), in which we perform the project management, undertake the design work, and supply the bogies and the major equipment while Sifang develops the new train cars. This scheme combines our technological capabilities with Sifang's low-cost production capacity. We aim to flexibly seek optimum partnering opportunities in the future, as well. In emerging countries whose infrastructure has not been well developed in spite of the demand for transportation, orders are often placed for entire railway systems, not just for train cars. To capitalize on this demand, we have been working to strengthen our system integration capabilities. Specifically, we are currently working on the Taichung City Railway System project, for which we won the order in 2011. In India, which is a new market for us, a freight-dedicated electric locomotive project is planned, and active marketing activities have been carried out.

In North America, we have a large backlog of orders,

Fig. 5 7000 Series subway cars for the WMATA

including 7000 Series subway cars for the Washington Metropolitan Area Transit Authority (WMATA) (Fig. 5), R188 subway cars for the NYCT, and M9 railcars for the Long Island Rail Road (LIRR) and the Metro-North Railroad (MNR). We will continue building a relationship of trust with our customers and actively strive to win orders for new projects by steadily implementing these large-scale projects using our production systems in Japan (Hyogo Works and Harima Works) and the United States (KRC and KMM), while also improving our productivity through the promotion of the Kawasaki Production System (KPS) and further enhancement of our supply chain management.

3 Technology development in the pursuit of originality and innovation

Our technological developments have led to the creation of a variety of vehicles, including Shinkansen (bullet trains), overseas train cars, and new transit systems. Given the Japanese and overseas market environment and the business developments described above, it is necessary to develop leading-edge technologies in the pursuit of originality and innovation that is unique to our company in order to successfully differentiate ourselves from other companies through non-price competitiveness.

We have developed efWING, a new vehicle bogie that uses CFRP for its main frame structure. The railcars used for efWING are made from carbon fiber reinforced plastic, which is a material often used in the aerospace field. This material's characteristics help to reduce weight significantly and curb energy costs. Through various demonstration tests conducted in the United States, efWING has been proven to meet the vehicle operational safety requirements of the US Department of Transportation (USDOT). After the development process was completed, efWING was put into operation by the Kumamoto Electric Railway Co., Ltd. in March 2014. Since fiscal 2015, the Shikoku Railway Company, the Kyushu Railway Company, and the Nishi-Nippon Railroad Co., Ltd. have conducted a series of operational tests to confirm the operational stability and passenger comfort. We will further improve this technology with the aim of achieving fully fledged commercialization.

In recent years, other railcar manufacturers have advocated the platform concept and demonstrated cost and quality advantages of scale by presenting manufacturer standards, similarly to in the automobile industry. However, we are focusing on the development of a scheme to respond to mass customization, in which value can be improved while continuing to meet customer requirements. The scope of application for efACE, the Company's standard railcar concept, has been expanding year by year to the point where it now covers railcars ranging from the initial aluminum railcars through to stainless railcars. We are also working to develop a module concept for overseas markets (Fig. 6), in which standard modules for parts and equipment, such as driver's cabs and doors, are built and assembled according to standardized procedures with the aim of making this concept applicable to overseas manufacturing while also meeting customer requirements.

For high-speed railcars, our proprietary flow analysis software was applied to resolve the aerodynamic noise being generated by pantographs and the lower parts of the carbody, and a large-scale analysis was performed using the K computer in Kobe city to clarify the cause of such

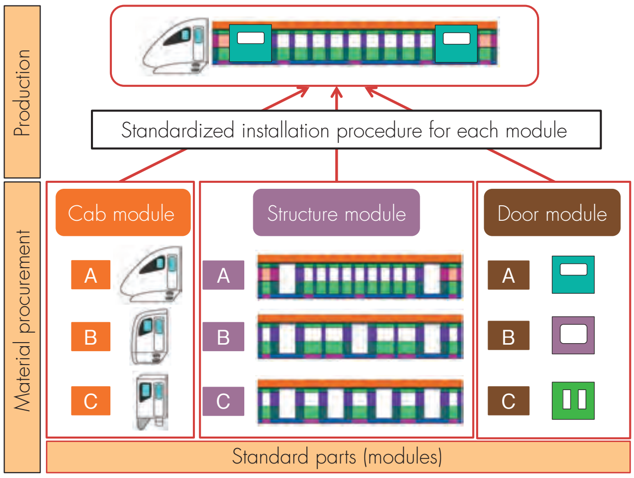


Fig. 6 Module concept

noise.

In overseas vehicle markets, we have succeeded in meeting strict technical and quality requirements, especially in our capacity as a pioneer in the North America market. For the latest 7000 Series subway cars for the WMATA, we have developed a thin corrugated floor structure to secure an additional underfloor outfitting space by reducing the floor thickness, while ensuring its rigidity, fire resistance, and heat and sound insulation. For the crash structure design, we have verified our analysis results by performing crash tests for the energy absorbing elements and then reflected the verification results in the design. These verifications have been front-loaded by intensively investing resources in the initial design process, and this has delivered significant results, such as the start of commercial operations as scheduled without any delays.

Meanwhile, as the Internet of Things (IoT) has attracted a great deal of attention, we have been working to develop the Bogie Instability Detection System (BIDS) as an underlying IoT-related technology. BIDS allows the information obtained to be continuously monitored, which contributes greatly to failure prediction diagnosis. We have also developed and started the mass production of a track irregularity inspection system that automatically detects irregularities in rail fastening parts and splice plates for commercially operated trains using image recognition technologies. This has contributed to cost reductions by improving the efficiency of track maintenance work.

4 Initiatives to improve customer satisfaction levels

Vehicle is effectively the face of the railway operators that make up our customer base. Reducing vehicle's environmental impact and life cycle costs, which is required more than ever recently, and providing rolling stock with improved designs helps to improve the corporate brands of railway operators. To improve customer satisfaction levels, we are working to increase passenger comfort through air conditioning and noise control. I would also like to describe the use of affective engineering and virtual reality, which have been studied in collaboration with Head Office's Corporate Technology Division.

Affective engineering is a technology that is used to objectively identify human feelings, so it can serve as an effective tool in creating design images based on the customer's design concept. Once design images have been created, they are converted into three-dimensional data, after which multiple designs created by our designers are verified scientifically based on affective engineering and developed into a concrete design. Finally, virtual reality (VR) using three-dimensional data allows the customer to check the three-dimensional design in advance for pre-verification. These initiatives to improve customer satisfaction levels have led to the acquisition of new customers.

In addition, since the Great East Japan Earthquake, there has been an urgent need for railway operators to address power outages and shortages. The solution is to secure infrastructure equipment in the event of an emergency. To this end, we have been focusing on enhancing the battery power system (BPS) by using Kawasaki's proprietary high-capacity nickel-metal hydride GIGACELL batteries, and we have delivered the world's first BPS for use in emergency train runs to Tokyo Monorail Co., Ltd. During normal rail operations, the BPS also stores regenerative electric power recovered from electric train cars, which allows railway operators to reduce their running costs by preventing regenerative invalidation.

Conclusion

Kawasaki Heavy Industries Rolling Stock Company has an operating history that stretches back over 100 years. During the past 15 years, the Company has achieved steady development, almost doubling its consolidated net sales, mainly due to an increase in overseas projects. We would like to thank our stakeholders for their continued support. Going forward, we would like to contribute to society by providing products that support safe, secure, and comfortable travel. To achieve that, we will continue to constantly strive to improve our outstanding quality and leading-edge technologies by making use of our integrated management to achieve further development.

Front Loading of Rolling Stock Design – WMATA7000 as a Case Study

Over the years, performance requirements of rolling stock design have become increasingly demanding. At the same time, the design of railway vehicles must be tailored to the existing facilities of railway companies, and manufacturers are increasingly asked to deliver on short lead-times. These trends were clearly evident in the project signed with the Washington Metropolitan Area Transit Authority (WMATA) in 2010 for the WMATA7000. To meet the challenging requirements, Kawasaki front-loaded design resources from the early stages of the project, which enabled it to achieve total optimization of design and delivery on a short lead time without delay.

Introduction

The performance required for rolling stock, such as safety, comfortable cabin environment, and operability, has grown more sophisticated with time. On the other hand, there are many constraints, such as space and weight, because new rolling stock is to be installed on the existing equipment of railway companies. The required performance significantly varies among railway companies. In addition, lead-time is becoming shorter and shorter.

For rolling stock, design items such as required performance and constraints that conflict with each other must be satisfied while ensuring entire projects progress without delay. To this end, front loading is effective for total optimization design and for shortening development and design periods. With front loading, sufficient resources are applied at the initial stage of projects.

1 Front-loading in rolling stock design

The rough flow of a rolling stock project is design, the purchase of raw materials and parts, production of pilot cars, various tests using pilot cars, and the mass production of cars. Any delay in the design may delay entire projects or force us to start subsequent steps even when the designs are not complete, which may result in reworking. Such reworking results in further delays in project schedules and deterioration of quality.

To avoid this, in front loading, importance is attached to the initial stage (the front) and thereby focusing resources in that stage (loading) to understand issues early, thus advancing development processes smoothly while also aiming at shortening lead-time, improving quality, and minimizing costs. In this report, we will introduce the WMATA7000 as an example case.

2 Outline of the WMATA7000 along with its design issues

Washington Metropolitan Area Transit Authority (WMATA) operates railways on six lines that extend into Maryland and Virginia with Washington, D.C. as its center. WMATA has approximately 1,300 cars from the 1000 to 6000 Series (six types). The operational start of the 1000 to 6000 Series varies from series to series, but they are compatible with each other so that train sets can be coupled for operation. The designs have also been standardized.

We received an order for 748 cars of the 7000 Series to replace existing cars and to add new cars. WMATA wanted to use stainless steel carbody structures (aluminum was used in the past), rooftop integrated air conditioning units, and Ethernet networks in the rolling stock. It also wanted to increase indicators in rolling stock and wanted the designs for the car interior and exterior to be novel. The requested items for the 7000 Series were new even for WMATA, so the series had high expectations as new rolling stock. Table 1 below shows the main specifications of the WMATA7000.

Issues with the WMATA7000 are listed below.

- WMATA was a new customer for us, so all of the rolling stock had to be optimized by making various conditions—such as car size, required conditions (e.g. strength, noise, and riding comfort), track conditions,

Table 1 Main specifications of WMATA7000

Car model		A Car, B Car
Dimensions	Total length [mm]	22,860 (75 feet)
	Maximum car width [mm]	3,092 (10 feet 1–3/4 inches)
	Maximum roof height [mm]	3,302 (10 feet 10 inches)
	Floor height [mm]	1,016 (40 inches)
Maximum speed [km/h]		120 (75 mph)
Acceleration [km/h/s]		4.5 + 0.3–0.0 (2.8 + 0.2–0.0 mph/s)
Deceleration [km/h/s]		4.8 ± 0.3 (3.0 ± 0.2 mph/s) (normal) 5.1 (3.2 mph/s) (emergency)
Carbody structure material		Stainless steel, low alloy high-tensile steel
Current collection method		DC700V, third rail
Braking		Air brake with regenerative braking Parking brake
Bogie		Air suspension bogie with bolster (inboard bogie) Axle box suspension: Laminated rubber
Side sliding door		Double-door with door pockets, three doors on one side Linear motor type door operator
Air conditioning unit		Rooftop integrated installation
Onboard network		ETN (Ethernet), TCN (MVB and WTB)

and the equipment to be installed on rolling stock—compatible with WMATA specifications.

- New cars had to be compatible with existing equipment. In addition, rig space had to be secured and weight had to be reduced because the equipment to be installed was increased to improve functions in comparison with existing cars.
- Detailed designs had to be completed one and a half years from when we received the order because the project's lead-time was tight.

3 Front-loading for the WMATA7000

In order to solve the issues in Section 2, we promoted front loading as discussed below.

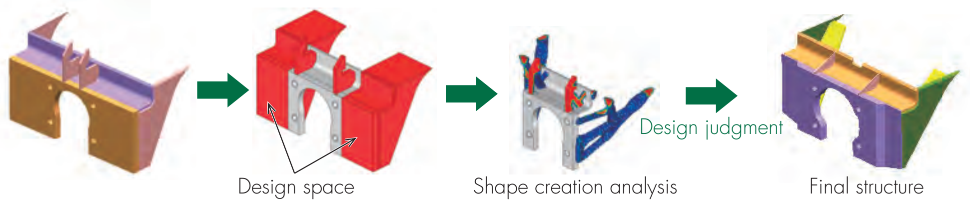
- The people in charge, who usually worked in each design section separately, were gathered in one place to do concentrated design.
- The Corporate Technology Division, which had a variety of key technologies, participated in the project from the beginning along with the Rolling Stock Company, which was the main entity for the development.
- Design resources were applied from the bidding stage as well as the initial stage after receiving the order to satisfy the high-level technical requirements, save weight, save space, shorten lead-time, and lower the price.
- The carbody structure, collision resistance, thin floor structure, air conditioning systems, noise, vibration, running performance and bogie strength, and electrical part systems were given primary consideration because they required time for discussion and they significantly affected downstream processes.
- Great importance was attached to concurrent engineering (a method in which design and production planning processes are carried out simultaneously) from the initial stage of development with an eye toward manufacturing.
- Design review was optimized and labor was reduced thanks to the introduction of new materials as well as structural developments and new development methods using advanced simulations.

(1) Carbody structure considerations (optimization calculation)

Weight saving is an important task in designing rolling stock. In the past, designers determined the thickness and shape of parts based on previous experience when designing carbody structures, identified sections where the strength was excessive or insufficient by analysis, corrected thickness and shape, and then performed analysis again. These processes had to be repeated several times.

This time, we used software to calculate the optimal thickness and shape and used the lists of increased and reduced thicknesses and optimal shapes obtained from the calculations, thus reducing the number of corrections to thickness and shape and the number of times the analysis had to be repeated (Fig. 1). Additionally, we were able to start the next step, designing part installation, quickly because carbody structure designs were completed early.

(a) Optimization of the thickness of carbody structures



(b) Optimizing the shape of the coupler bracket

Fig. 1 Investigation of carbody structure (optimization analysis)

(2) Carbody structure considerations (collision)

High collision resistance is required in designs for North America. The design suitability was verified and evaluated by collision analysis in order to meet various conditions, such as absorption of collision energy, securing survival space when leading cars were deformed due to collision, derailing, and running aground (Fig. 2).

In addition, we carried out crash tests for collision energy absorber elements and collision tests for frame structures. We verified the analysis results and incorporated the results in our designs. Thanks to the work and tests above, the collision resistance structure was determined at an early stage, making it possible to start the production of carbody structures without delay.

(3) Thin floor structure

The space under the WMATA7000 floors was small, so the floor structure had to be made thinner to secure space for the installation of underfloor equipment, pipes, and wires. In addition, after the floor structure was determined, designs for underfloor equipment, pipes, and wires were started, so the floor structure had to be determined quickly. Usually, thinner floor structures act against stiffness, strength, fire-resistant and heat-insulating properties, and sound insulation performance. However, we developed a new thin corrugated floor structure that can satisfy the performance required while reducing floor thickness. The new floor structure made it possible to secure space to rig underfloor equipment, pipes, and wires (Fig. 3).

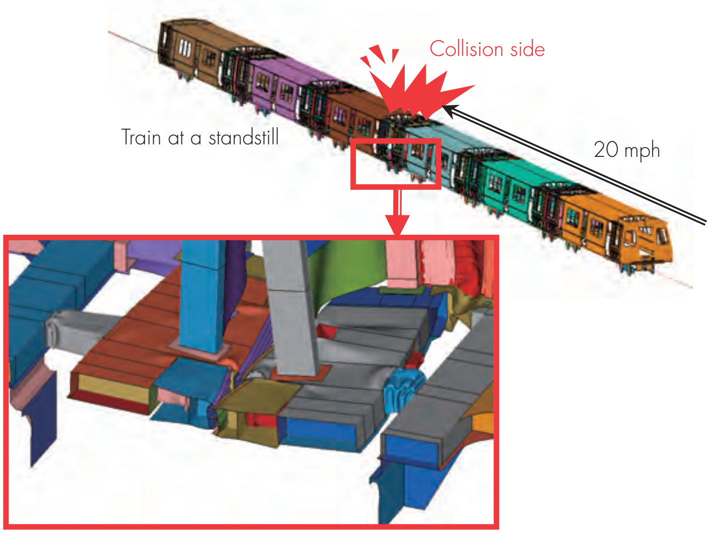


Fig. 2 Investigation of carbody structure (collision analysis)

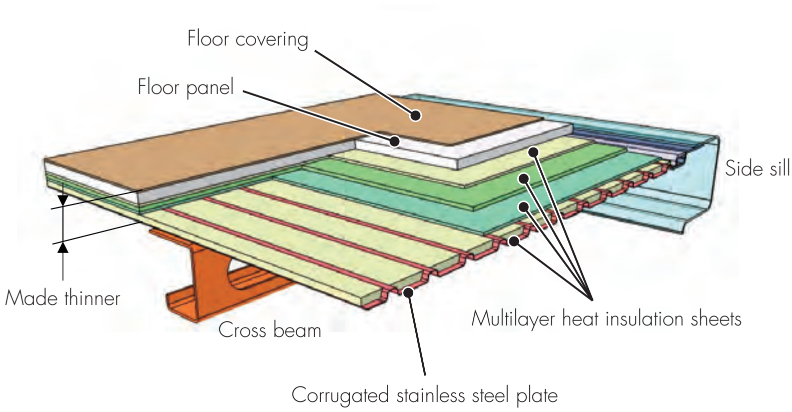


Fig. 3 Investigation of floor construction

(4) Air conditioning system (Optimization of air quantity and temperature in cars and reduction of noise)

Ducts had to be designed so that the specified air quantity was achieved based on the performance of the air conditioning units and spaces in the ceiling cavities. At the same time, air conditioning temperature distribution had to be optimized and noise had to be reduced. Rooftop integrated air conditioning units, which are easy to maintain, were used for the WMATA7000 (the separate type, where units were installed on the rooftops and underfloor, were used in existing cars). However, the size of the new cars was the same as existing cars, so the air conditioning units and ducts had to be installed in very limited spaces in the ceiling cavities.

Therefore, by making full use of simulations using computational fluid dynamics (CFD) analysis, we were able to study designs that could optimize air quantity distribution in the air conditioning ducts and passages, make the temperature distribution in cars appropriate, and reduce noise (Fig. 4). An actual car was used in a test for the final evaluation of the air conditioning system in a climatic testing room. Any problems found at that time would have affected the designs and production of other sections. However, the early-stage simulation prevented large-scale reworking.

(5) Interior Noise

Interior noise is judged based on the results of measurements at the actual sites after cars are delivered. If the noise levels at that time are beyond the specifications, the cars must be redesigned, which would affect the delivery schedule. Therefore, the statistical energy analysis (SEA method) was used to simulate noise prior to the delivery of the WMATA7000 (Fig. 5). Rolling noise around bogies under the influence of rails was required as input data for such simulations, so we used existing cars to get measurements and used the obtained data for the simulations. The noise levels were within the specifications in the measurements conducted after the WMATA7000 cars were completed, so no rework was required.

(6) Carbody design (cab design)

When cabs are designed, considerations are necessary to ensure the operability of equipment and to secure a forward view for drivers with different physical features based on ergonomics. In the past, two-dimensional drawings were used for such verification, but there were limitations on the verifiable scope. Therefore, three-dimensional models were used for the WMATA7000 to verify in detail the operational range and view in consideration of the differences in the physical features of

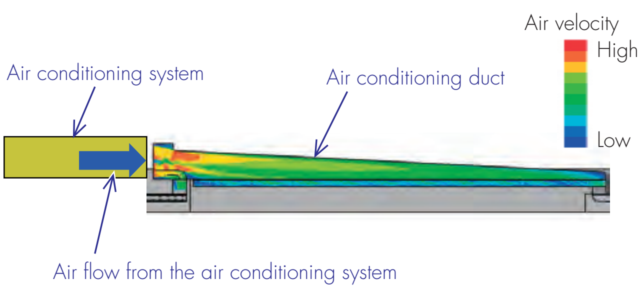


Fig. 4 Investigation of HVAC system (air distribution)

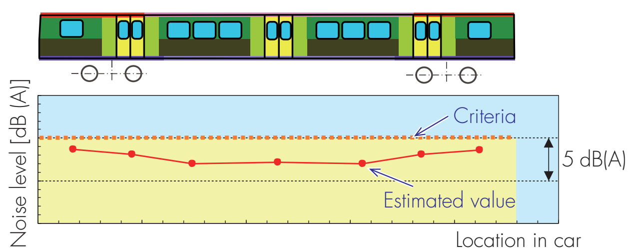


Fig. 5 Investigation of interior noise

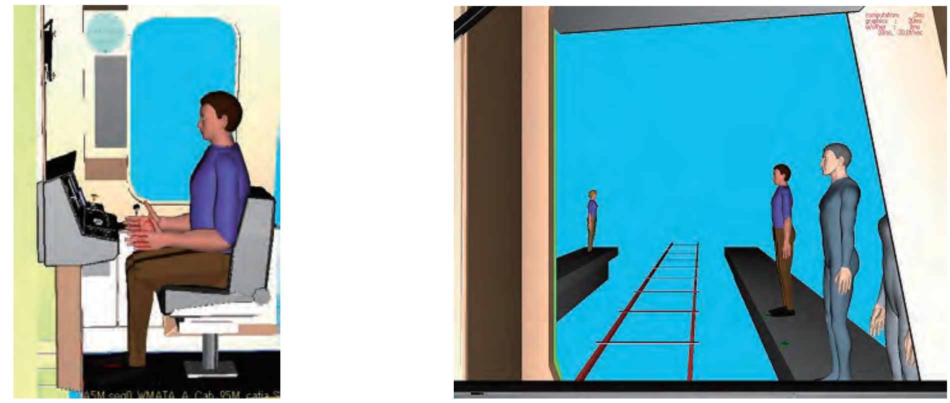
drivers (Fig. 6). We were able to check details using the simulation results prior to the production of a mockup, thus shortening the design period and making it easy to carry out visual checks, enabling us to obtain customer approval earlier.

(7) Bogies (running simulation)

In bogie design, it is necessary to check if the running performance reaches required levels and if running safety is ensured in running simulations in the design stage beforehand. Many items and conditions need to be evaluated, but bogies are to be designed in a detailed way based on the simulation results, so such evaluation needs to be carried out effectively in the initial stages of projects. We carried out many simulations for each of the combined conditions in an efficient way and incorporated the results in the bogie designs (Fig. 7).

(8) Bogies (consideration of strength)

Various loads are applied to bogies. Static strength and fatigue strength must be closely inspected for all combinations of a variety of loads in order to secure safety. We have developed a new system that combines various loads to calculate the strength and optimizes thickness based on the results and used it to design the bogie frames and bogie bolsters for the WMATA7000 (Fig. 8). This system made it possible to reduce the weight of the components while maintaining sufficient strength and it allowed us to shorten the design period and to continue to the next process smoothly.



(a) Verification of operation range (b) Verification of view

Fig. 6 Carbody design (cab)

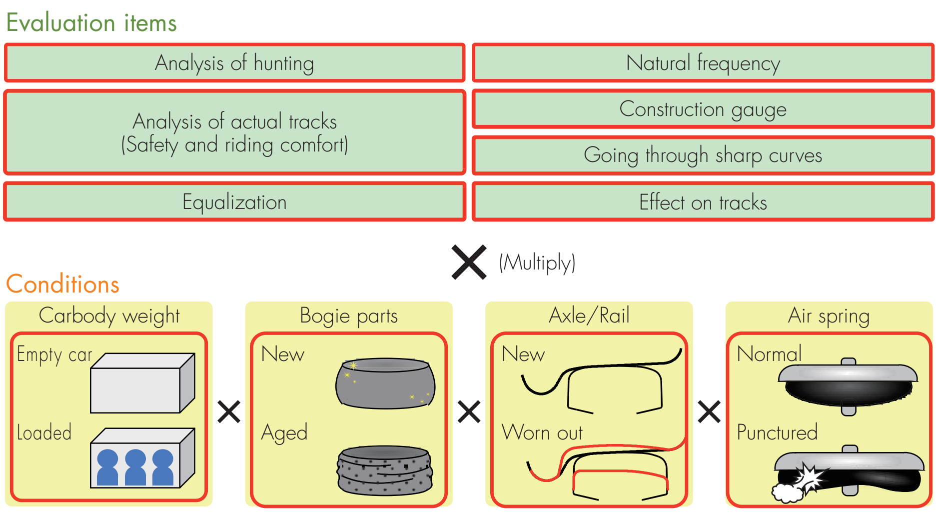


Fig. 7 Bogie design (running simulation)

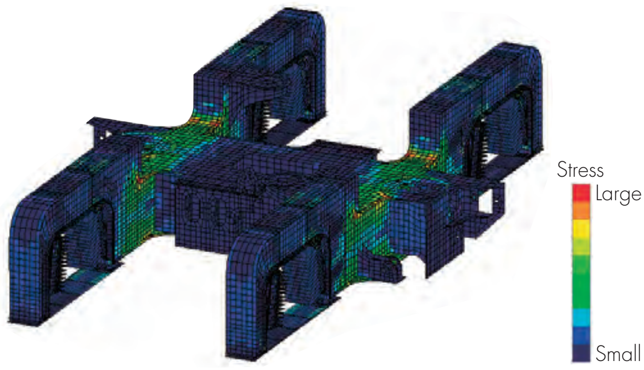


Fig. 8 Bogie design (strength investigation)

(9) System design

The amount of equipment to be installed on the WMATA7000 was greater than existing cars, including network devices and passenger information system. Advanced functions were also required. If the specifications for the equipment are changed after being decided, designs for installing such equipment must be reviewed. To avoid this, we had focused meetings with equipment manufacturers from the start of the project and designers working on the system and equipment installation (designs of car bodies, rigs, and bogies) engaged in detailed discussions about the designs while continuing the design work, which reduced the amount of rework required.

(10) Concurrent engineering

Even when designs satisfy customer specifications, if difficulties are encountered in manufacturing the products, they must be redone. Therefore, we used concurrent engineering wherein manufacturability was discussed with the engineering sections from the beginning of the WMATA7000 project.

Conclusion

In this report, we introduced a project with front loading in rolling stock design using the WMATA7000 as an example. Applying design resources from the start of the project allowed us to complete the designs in a shorter period of time without much rework. In addition, it was highly effective for total optimization. Furthermore, newly developed simulation techniques and the like significantly contributed to energy saving and optimization. We will apply these methods in the future as well to the new model rolling stock for other companies that we are currently researching in order to satisfy requests that are growing more and more advanced.

The WMATA7000 cars went into service in April 2015 after finishing the designs, the manufacturing of prototype cars, and various tests. Currently we are manufacturing and delivering mass production cars.

Last but not least, we would express our appreciation to everyone at WMATA and the equipment manufacturers for their cooperation from the initial design stage.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Global Expansion of efACE Standard Railcars

Kawasaki's efACE standard cars combine the concept of a standard car and flexibility. In the Japanese market, Kawasaki made full use of this flexibility by expanding the application of the efACE model to both aluminum cars and stainless steel cars.

With an eye to capturing new customers and market share in overseas growth markets, Kawasaki is currently developing standard cars for overseas users based on the existing efACE technologies for the Japanese market.

Introduction

Recently, requests from railway companies (customers) have been diversifying with increasingly shorter delivery schedules and ever lower prices. For this reason, trains had to be standardized and diversifying customer needs had to be met in a flexible way.

1 efACE standard cars

We have been developing environmentally friendly advanced commuter and express train cars known as "efACE" as proposal-based standard cars that meet various user needs.

The efACE standard car is a well-balanced car that anyone can be satisfied with, whether passengers, railway companies in charge of operation and maintenance, or car builders, all of whom evaluate the cars from their own standpoint.

Conventional standard cars that were developed mainly by car builders gave high priority to manufacturing processes and cost reduction, so they were not necessarily satisfactory to users and railway companies.

However, reducing manufacturing costs results in reduced costs for the railway companies purchasing the train, which also benefits passengers as they have more opportunities to ride in comfortable new trains, for example.

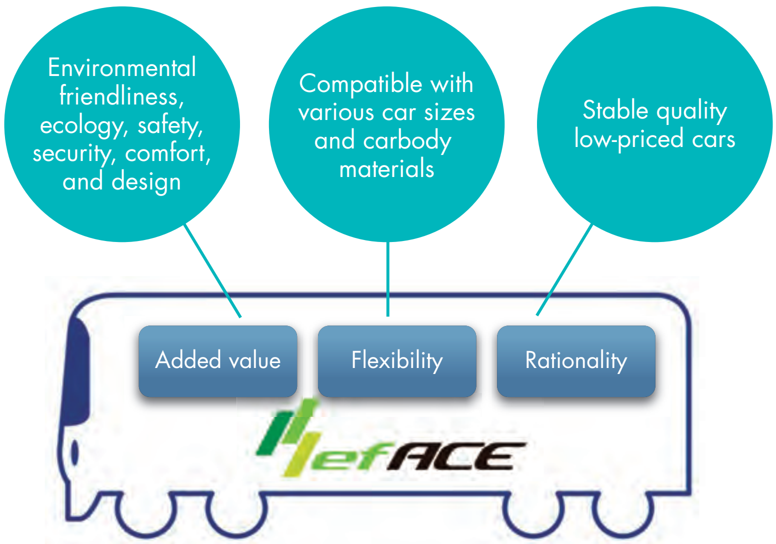


Fig. 1 Basic concepts of efACE standard cars

We have established three basic concepts according to which we produce our efACE cars, namely added value, flexibility, and rationality, in order to maintain the benefits for people in each standpoint even though they are low-priced standardized cars (Fig. 1).

Added value means safety, comfort, and design. Flexibility refers to compatibility with various car sizes, applications, and carbody materials. Rationality represents stable quality, low-priced cars, and so on.

These three basic concepts have often been neglected in the development of standard car by car builders, but these concepts are always given high priority from the planning stage of an efACE car.

This is especially easy to see in terms of "flexibility," one of the basic concepts of efACE. The ability to satisfy various user needs is a given, but efACE goes beyond that with flexibility for car builders. For example, these cars can be made with any carbody material, body structure, and manufacturing method used by car builders. This means that efACE trains can meet user needs that vary from company to company and that affect the basic structure of cars, such as the sizes of cars and side windows, the materials used for the carbody, the locations of doors, and the number of seats.

2 Applications of efACE in the Japanese market

efACE cars were first used for the 3000 Series electric trains for Keihan Electric Railway Co., Ltd. as aluminum commuter trains. After that, the use of efACE trains expanded to stainless steel commuter trains and stainless steel suburban trains by utilizing their flexibility.

Let us introduce some actual cases in which aluminum and stainless steel cars were used.

(1) Aluminum cars

An aluminum car (Fig. 2) is an assembly consisting of underframe, side, roof, and end body structure blocks for which many extruded sections are used.

For the aluminum body structures used in efACE, the cantrails placed at both ends of roof body structures and the side sills located at both longitudinal edges of underframe body structures are flexible parts. That is why

3000 Series used by Keihan Electric Railway Co., Ltd.

16000 Series used by Tokyo Metro Co., Ltd.

Fig. 2 Trains featuring aluminum efACE cars they are able to meet varying user needs such as different roof heights and car widths (Fig. 3).

A side carbody structure consists of body structure parts with a harmonica shape as shown in Fig. 3. This structure is common to all of our models. The harmonica structure has flexibility that makes it possible to meet various user needs such as different types of car interior equipment and various installation locations without changing side body structure parts.

(2) Stainless steel cars

For a stainless steel car (Fig. 4), stainless steel skins, frames, roll-formed long parts, etc. are assembled by spot welding and/or laser welding to make the underframe, side, roof, and end body structures.

In an efACE stainless steel body structure, the shape of a frame installed onto the side body structure in the longitudinal direction of the car is the same as that of the harmonica structure of the aluminum body structure, making the procedures for installing the interior parts the same for both aluminum and stainless steel body (Fig. 5).

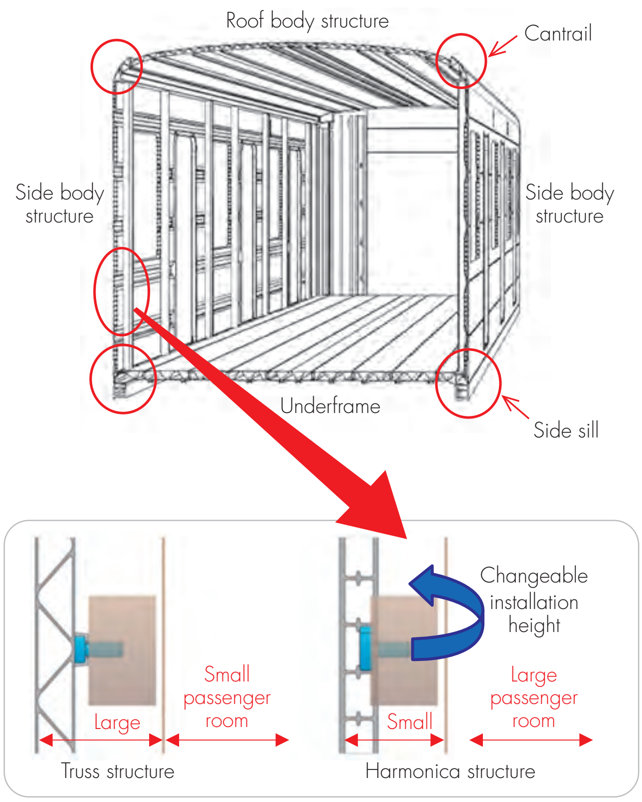
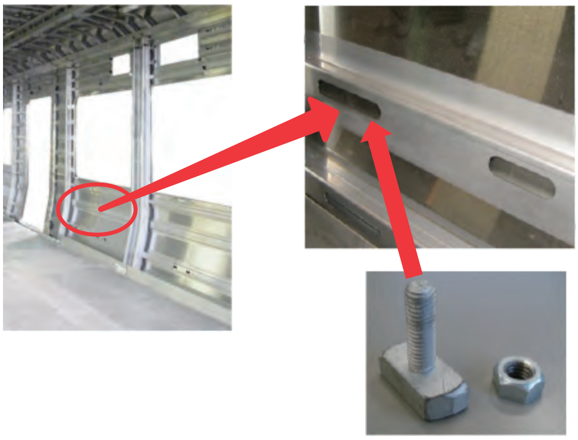


Fig. 3 Cross-sectional structure of an aluminum efACE car

225 Series used by West Japan Railway Company

733 Series used by Hokkaido Railway Company

Fig. 4 Trains featuring stainless steel efACE cars



Bolt that is also used for aluminum cars

Fig. 5 Interior mounting structure of a stainless steel efACE car

3 Concepts for developing efACE for overseas

When we developed efACE for overseas to satisfy needs, such as the need for increased local production (which has been growing recently), we kept the same three basic concepts while redefining them for overseas as shown below.

Added value ⇒ local production
Flexibility ⇒ flexibility of equipment, procurement, and manufacturing methods
Rationality ⇒ modularization

In addition, the catchphrase

"Anywhere, Anyone"

was announced to allow development team members to share a more specific image of the development concept (Fig. 6).

(1) Anywhere

Various special facilities are required to manufacture cars because of their length. To avoid using such special facilities, cars have to be divided into shorter parts that are then connected, that is to say that cars must be modularized.

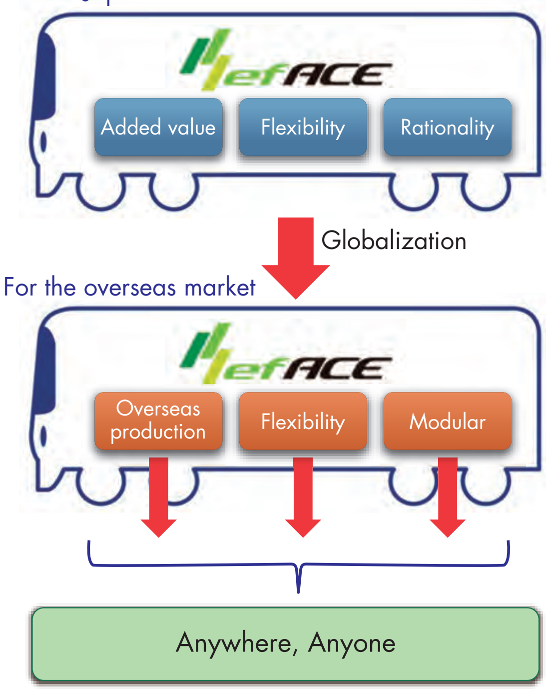


Fig. 6 Development concepts of efACE for overseas

These shorter modularized components can then be procured from new external suppliers instead of existing car builders that specialize in long objects.

In addition, special ground facilities that car builders owned had to be used in the assembly processes for forming the box-shape of the car in the past. We have developed a joining method and special tools that do not require such special ground facilities.

(2) Anyone

Conventional cars were manufactured by relying on the skills of expert engineers such as welders, sheet metal workers, electricians, and plumbers. It is difficult to have local manufacturers and external procurement sources acquire such technical skills in a short period of time. Therefore, new manufacturing methods that do not rely on operators with specialized skills are required.

The sizes of modularized components were determined based on the sizes of the finishing machine tables that ordinary factories owned. Manufacturing processes were mechanized to make it possible to manufacture cars without relying on human skills. In addition, methods for joining components were changed from methods that rely on operators' skills to methods for which tools could be used to perform and manage the joining process.

For wiring work, we only used harness modules to eliminate the work of adjusting the length of wires in the cars and attaching pins to terminals. Because of this, the only work that has to be done in cars is to install the harness modules that were manufactured somewhere else.

(3) Rigging unit

Rigging in car manufacturing refers to installing fixtures, wires, and devices onto cars.

In the standard design process of the past, the car strength, which is a basic requirement of train performance, was given priority and then the design of the rigs was started. In the development of efACE for overseas, rigging is considered from the initial planning stage, including division units between modules of each component and each location.

In the past manufacturing methods, it was not possible to unify division locations, joint methods, and an order of manufacturing processes for the module unit best-suited to rigging and for the module unit best-suited to car strength. Therefore, we changed the manufacturing processes taking the limitations in each manufacturing process into consideration to determine the best module divisions. This made the prefabrication of each module possible.

4 Manufacturing a mockup of efACE for overseas

We manufactured a mockup to verify if the cars that were planned and designed under the above catchphrase could be actually be made (Figs. 7 and 8).

When the module components of each body structure were manufactured, special facilities that car builders own were not used. Only facilities that ordinary sheet metal factories have were used.

When the carbody was assembled, ground facilities

Fig. 7 Exterior of an efACE mockup car for overseas

Fig. 8 Interior of an efACE mockup car for overseas

that car builders owned were not used. We only used the simple special tools that we had designed and developed.

For the interior parts, we freed ourselves from conventional materials for car interiors and we placed orders to new suppliers using architectural materials and resins. Not being bound by conventional methods, we took a hint from the methods for installing appliances used in the construction of stores and we modified them for use in our cars.

In order to verify if the "anyone" part of the catchphrase was true, the persons who had developed and designed this car themselves performed part of the installation in this mockup. This design has eliminated the need for adjustments by skilled workers that were required in conventional work on the interior, so the completed section looks no different from the sections that were manufactured by our skilled workers.

The elemental technologies that we acquired by producing the mockup efACE car for overseas have been gradually fed back into efACE for the Japanese market. The mockup of efACE for overseas for which flexibility was most effectively used showed that the flexibility of efACE for the Japanese market could be further expanded. As a result, we came to be able to accurately and flexibly meet the recent high-level user needs stemming from efforts of companies in the Japanese train market to differentiate themselves from the competition.

Various efACE elemental technologies have been adopted in the new trains we currently are designing.

Conclusion

It was found that our efACE standard cars are highly flexible, in line with the aim of its concept, and that they can also be used overseas.

In addition, we found that the flexibility of the efACE for overseas currently being developed can be expanded further and fed back into projects in Japan along with high-level technologies for conventional trains for overseas.

We will continue to progress in our development to meet the needs of users in Japan and around the world.

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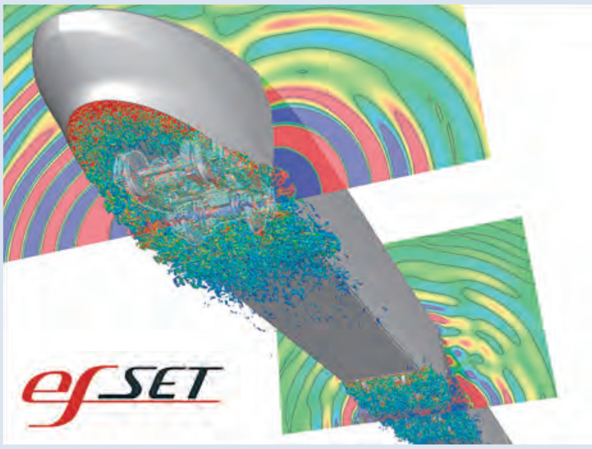
Development of High-speed Trains that Deliver "More Speed"



In meeting customer demand for faster trains, developers must also focus on achieving noise reduction and the development collision resistant structures. To this end, it is vital that noise and crash events are accurately reproduced in simulations and that they are used to perform thorough validation in advance.

Recently, we succeeded in reproducing these phenomena in the development of a high-speed train currently underway at Kawasaki. This was achieved through aeroacoustic simulations using the K computer and crash analyses using the finite element method (FEM). These technologies are expected to further accelerate the development of high-speed trains.

Introduction

Significant reductions in time spent travelling for business and leisure purposes are expected to further stimulate economic activities, bringing about greater economic growth. Therefore, demand for faster trains is increasing, not only in Japan but also for all the railways of the world.

1 Background

In recent years, there has been an increase in the momentum of the development of higher-speed Shinkansen and the introduction of high-speed railways in other countries. Under these circumstances, it can be said that the challenge of achieving "greater speed" boils down to two major factors: noise reduction and collision resistance.

Noise is generated mainly from pantographs and the lower part of carbodies. Greater speed will entail an increase in rolling noise and an even greater increase in aerodynamic noise. The former increases roughly with the cube of the speed, and the latter with the sixth power of the speed.

We have already made repeated efforts to identify the characteristics of noise produced by pantographs manufactured to overseas market specifications and to verify the analytical precision of comparisons against wind tunnel test results. Consequently, although we have qualitatively confirmed that the peak frequencies often match, we have not yet truly succeeded in making quantitative predictions for sound pressure levels due to the lack of grid resolution. In addition, noise from the lower part of carbodies contributes significantly more than that from pantographs, as overseas high-speed railways do not always have exclusive use of tracks or sound abatement walls while Shinkansen has those specifications and it is common in Europe for bogies not to have lateral covers or to be half-covered. Nevertheless, in the past, we did not carry out large-scale aeroacoustic analysis of noise from the lower part of carbodies using the real-life lengths of carbodies (3 or more carbodies), because detailed modelling of the sound source (bogies) was difficult and it has also been virtually impossible for any of our existing computational resources to do such analysis.

However, we have now begun to make use of the K computer to improve the accuracy of quantitative predictions about aerodynamic noise generated from pantographs, as well as to conduct research to predict aerodynamic noise generated from the lower part of high-speed railway carbodies through advanced large-scale unsteady computational fluid dynamics (CFD) analysis.

On the other hand, in the development of a collision-resistant structure, overseas railway carbodies are required, by standards, laws, regulations and specifications, to meet given collision resistance requirements. A typical example is the European collision resistance requirement standard EN15227, which requires carbodies to provide a reasonable level of survivable space in the event of a collision between two railway cars and a reduction in speed at the time of the crash. It is also expected that a collision resistance requirement will be added to the Code of Federal Regulation (CFR) in the United States for railway cars with a maximum speed which is 201 km/h or faster and slower than 354 km/h, with a view to ensuring safety for high-speed railways.

Railway car manufacturers are required to provide proof that their cars meet these requirements. However, it is difficult, both economically and physically, to conduct crash tests using the real-life lengths of carbodies. This is why it is now acceptable to prove collision resistance by conducting crash analyses and tests that demonstrate the analytical accuracy in line with the scenarios of the requirements mentioned above. Consequently, numerical simulation-based crash analysis has become an important technical tool for validating the collision resistance of cars.

2 Aeroacoustic simulations using the K computer

(1) The unique analytical method used by Kawasaki

The CFD software used in this study is "Cflow" which is developed by Kawasaki. Cflow consists of an automatic grid generator that allows for dealing with complicated geometries and a flow solver that employs low-dissipation scheme to capture unsteady flow characteristics and aerodynamic noise. This software has already been ported to the K computer, and parallelization has been carried out for super-scale analysis, for example through increasing the linear computation speed to enable parallel computation on thousands of cores. Although the original purpose of the software was to evaluate the aerodynamic performance of aircraft, new functions have been added in recent years to make it more applicable to railway cars, including those related to tunnel micro-pressure wave and cars passing each other, with the aim of expanding its scope of application to the products produced by Kawasaki.

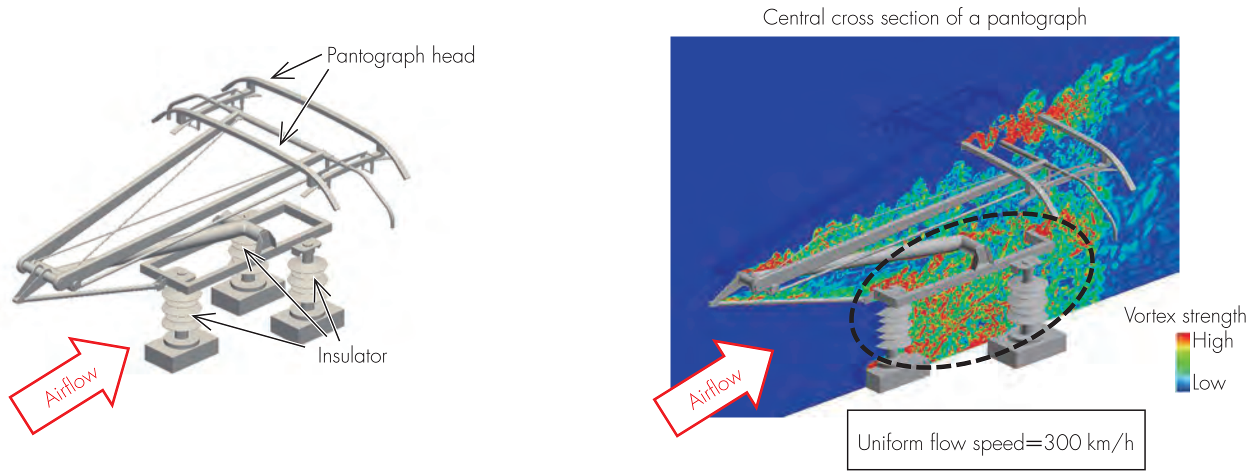
(2) Aeroacoustic simulation of a pantograph

Figure 1 (a) shows computational model of a pantograph. The computational grid consists of 410 million cells to achieve a higher grid resolution compared to the conventional grid of 153 million cells. The computational resources of the K computer, which we used this time, were equivalent to 2,048 cores (256 nodes). The speed of uniform flow is set at 300 km/h according to the conditions for the wind tunnel test.

Figure 1 (b) shows the vorticity distribution (instantaneous values) observed in the plane of the central cross-section to identify the areas that contain vortices. Wake vortices from the insulators are captured in detail in the area indicated by dotted lines.

Figure 2 shows the comparison of the sound pressure level (SPL) at a far-field observation point (25 m from the pantograph). The computational results we have obtained this time for SPLs at frequencies of 125 Hz–800 Hz, including those at the two peak frequencies (160 Hz and 315 Hz), which we had not been able to quantitatively predict in the past, are closer than ever before to the measurement results from the wind tunnel test.

Moreover, the precision of analysis has also improved at high frequencies of 1 kHz and higher. Thanks to the



(a) Computational model

(b) Isosurface of vorticity magnitude

Fig. 1 Aeroacoustic simulation of a pantograph

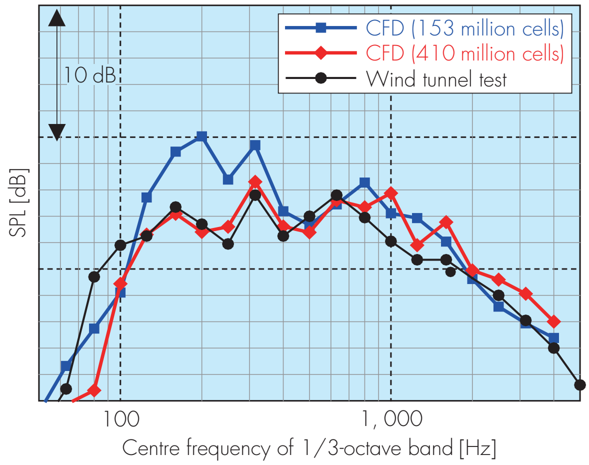


Fig. 2 SPLs at a far-field observation point

increased grid resolution, we have succeeded in improving the accuracy of quantitative SPL predictions.

(3) Aeroacoustic simulation of the lower part of "efSET"

(i) Computational conditions

The computational model is "efSET" with three (leading, intermediate and rear) cars which Kawasaki had developed for high-speed railways. As shown in Fig. 3 "Bogie (enlarged)," the radius arm type high-speed bogies[1)] for the 1.5 cars in the front were modeled in detail. Regarding bogie covers, only the first one from the front of the train had a full cover (covered), and the remaining bogies had a half cover (non-covered). The computational model is on a real-life scale, with a 26.4-meter-long leading car and an inter-car distance of 0.5 meter.

Two types of computational grids were created, one with 832 million cells and one with 169 million cells (for checking the effect of bogie covers). Fine grids were placed in the car and inter-car areas to detect vortices, while relatively fine grids were set up in the upper and side areas of the cars to detect the propagation of sound waves. The train speed is set at 350 km/h to simulate a real-life running train. For the 832 million-cell computation, the 8,192 cores (1,024 nodes) of the K computer were used.

(ii) Computational results

Figure 4 shows the isosurface of vorticity magnitude (instantaneous values) to identify the areas that contain vortices. Strong vortices are generated by the edge of the skirt at the front of the train. The bogie areas are mostly where the turbulent flows are, while fine vertices are generated also from the entire bogie areas between the leading and intermediate cars. However, vortices generated by the bogies at the back of the leading car and at the front of the intermediate car are not as strong as those generated by the first one at the front of the train. Besides these, vortices are generated also by the lower part of the carbodies between the cars, which have not been observed in the conventional computation due to a lack of grid resolution.

Figure 5 shows the surface SPL distributions at 400 Hz on the surfaces of the leading carbody and bogies. Marked fluctuations are observed at the lower part of the carbody, where flows separated from the edge of the skirt become attached again. In addition, high level of pressure fluctuation is also observed on the outer surfaces of the

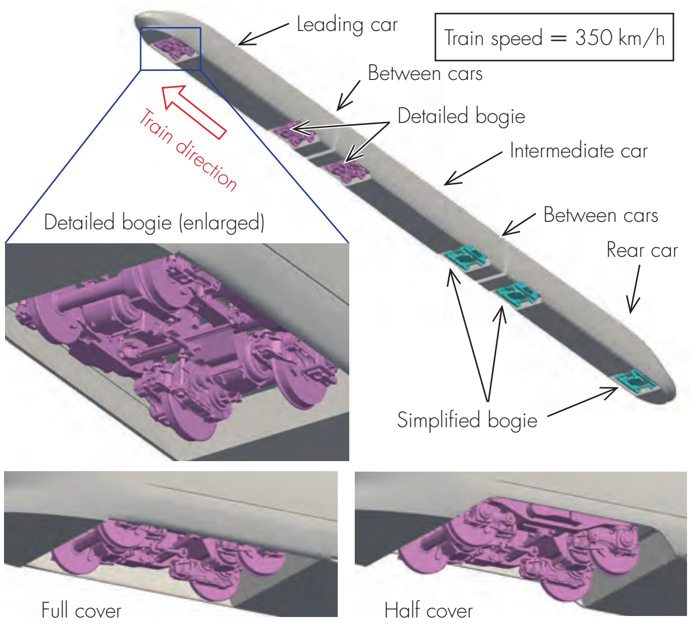
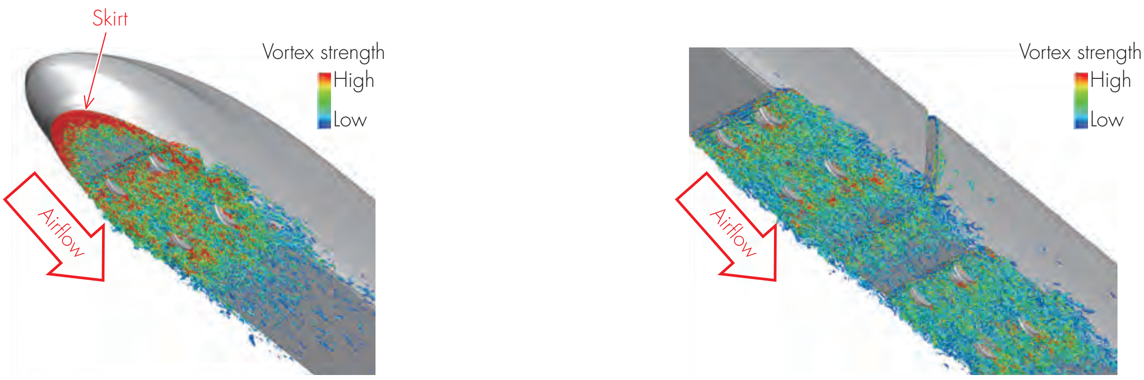


Fig. 3 Computational model (bogie)



(a) Leading car　　(b) Between the leading and intermediate car

Fig. 4　Isosurface of vorticity magnitude

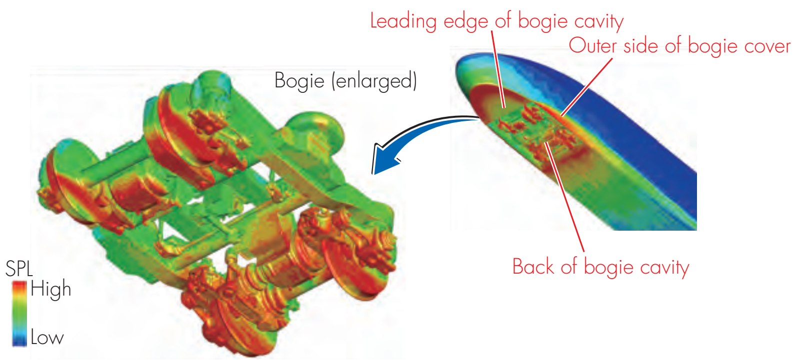


Fig. 5　Surface distributions of SPL at 400 Hz

bogie covers and at the back of the bogie cavities, while exposure to shear layers generated from the leading edges of the bogie cavities also causes significant pressure fluctuations on different parts of the bogies (wheels and machines). On the whole, aerodynamic noise is expected to be generated by the wide areas of the bogies.

Figure 6 shows the results of extracting and visualizing pressure fluctuations at 100 Hz via band-pass filtering, at a height of the upper surface of the tracks. In this figure, the red and blue short bands indicate that pressure waves fluctuated with fluid movement and the red and blue longer and blurry bands represent the propagation of sound waves towards outer areas. In this way, sounds radiating from the bogies are oriented towards the sides.

Lastly, we also examined what difference there is between when the bogies are covered and when they are not, as it is common in Europe for bogies to not have covers or be half-covered. The first car from the front of the train was half-covered in order to check the effect of bogie covers. Figure 7 shows the comparison of the sound pressure levels at a near-field observation point. As a result of the comparison, it is analytically confirmed that the noise level decreases at all frequency spectra when the bogie is fully covered, resulting in an overall reduction of 2.4 dB (A). As detailed modelling and super-scale analysis of bogies have become possible, we can now apply this to the noise evaluation of bogie covers.

※The carbodies are displayed as transparent.

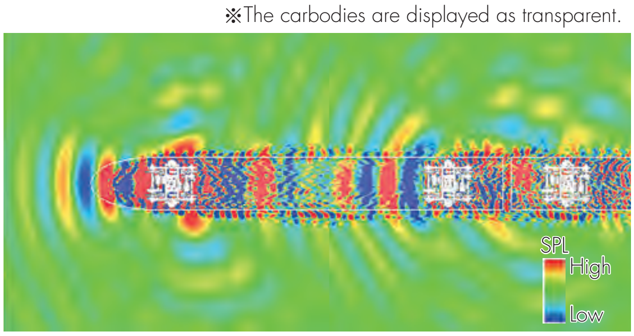


Fig. 6　Filtered pressure fluctuation at 100 Hz

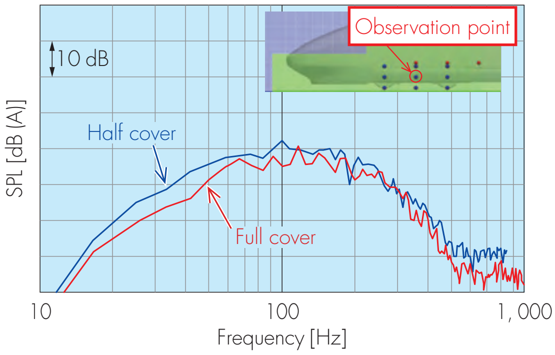


Fig. 7 SPL at a near-field observation point

3 Crash analyses using the finite element method (FEM)

(1) Demonstration of the collision resistant structure of "efSET"

We have been working on the development of a collision resistant structure that conforms to EN15227 and CFR as elemental technology for efSET[1]. For efSET, to meet various requirement specifications, we have clearly distinguished between a zone for crash energy absorption and a zone for providing survival space for crew and passengers, and have developed a collision resistant structure based on the concept of modularizing crash energy absorbing elements. Simulation-based evidence for the collision resistance of this structure is certain to give Kawasaki a powerful competitive edge in attracting orders for train cars for overseas high-speed railways. Therefore, we have created a crash energy absorbing element and a head structure, based on the results of the examination of the distribution of energy absorption sites for overseas market specifications, and carried out a crash test for analysis. In the test, the head structure to which the energy absorbing element was attached was fixed to a steel wall, and a crash bogie with an estimated level of crash energy was crashed against the head structure at a speed of 60 km/h, as illustrated in Fig. 8.

(2) Crash test results

This structure requires that in the event of a crash, only the crash energy absorbing element should deform to absorb the resulting crash energy, so that the survival space zone can be protected. As the deformation diagram in Fig. 9 indicates, both the test and simulation results show that the post-crash behaviour of the structure was in

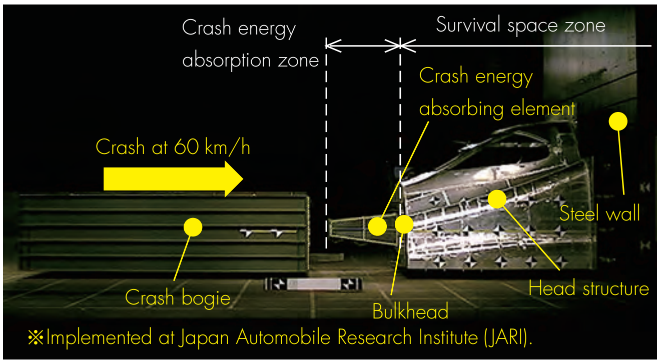


Fig. 8 Crash test

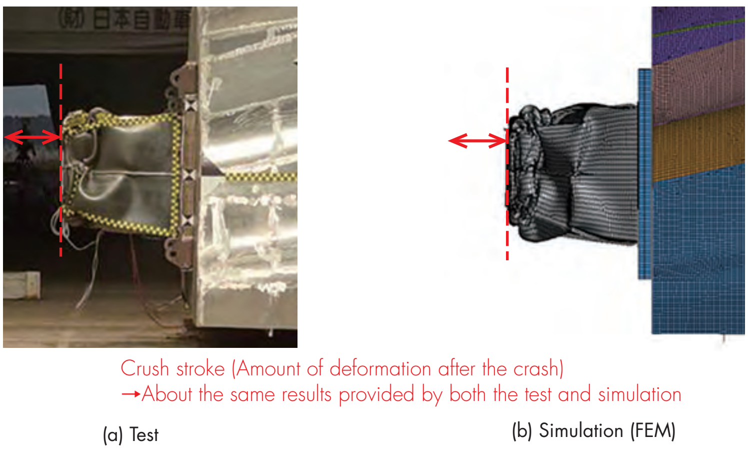


Fig. 9 Deformation diagram

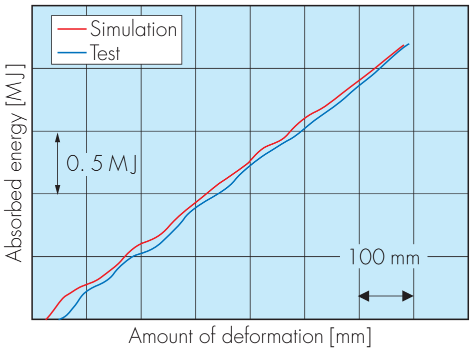


Fig. 10 Absorbed energy diagram

line with the above concept and that the structure has a satisfying level of collision resistance. Additionally, the state of deformation and the crush stroke of the crash energy absorbing element conformed to the results of the simulation performed in advance. A comparison of the amounts of absorbed crash energy of the crash energy absorbing element, shown in the diagram in Fig. 10, also confirmed that the simulation and crash test had about the same results.

Conclusion

We carried out large-scale analysis of aerodynamic noise using the K computer, by applying our internally-developed CFD software "Cflow" to the aerodynamic noise from the pantograph of a high-speed railway car and from the lower part of "efSET," which was also developed by Kawasaki. Our next task is to further improve analytical precision, while at the same time exploring effective noise reduction measures targeting the noise generation sources themselves by evaluating noise at a far-field observation point and identifying the dominant sites.

Our crash test results also showed the high precision of the collision resistance simulation in the crash analyses using the finite element method (FEM).

We aim to continue making these analytical technologies more and more sophisticated in order to accelerate our development of high-speed railway cars.

The "aeroacoustic simulations" mentioned in this article used the computational resources of the K computer provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Project ID: hp140057 and hp150059). We would like to express our gratitude to RIKEN here.

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efWING
– New-Generation Railway Bogie

Part of the frame of this railway car bogie is made of CFRP (Carbon Fiber Reinforced Plastics). In addition, the CFRP frame is designed to function as a coil spring suspension as well to integrate two functions into one. efWING is the world's first railway car bogie that uses carbon fiber, i.e., an advanced material that has been used for aircraft. By taking advantage of the material's properties, a substantial weight reduction has been achieved so as to enable the cost of operating energy to be reduced.

Introduction

Recently, in consideration of global environmental issues, there has been a growing trend to save energy. Under these circumstances, railway cars are also expected to save energy. The most effective way to save energy, in other words, reduce running costs and CO_2 emissions, is to reduce the weight of railway cars.

1 Background

A railway car is divided into two parts, namely, a carbody and a pair of bogies. For the carbody shell, which carries passengers and cargo, substantial weigh reductions have been achieved by using stainless steel, aluminum alloys, and other materials. On the other hand, for the bogie, which takes on the role of running, optimization analysis techniques based on numerical simulations, including the finite element method, have been leveraged to implement weight reduction measures by means, for example, of reducing the plate thickness and providing the weight reduction holes, to date. In recent years, however, there has been a tendency for bogies to be equipped additionally with a variety of devices and components, including damping equipment and sensing devices, to improve railway car's running performance as well as condition monitor for railway car. Such devices and components contribute to weight increases and no further weigh reductions can be easily achieved by existing measures. For this reason, there has been a need to fundamentally change the conventional design concept.

Meanwhile, applications of composite materials are steadily expanding not only in the railway car industry but also in the aviation and motor car industries from the viewpoint of weight reduction. For example, CFRP (Carbon Fiber Reinforced Plastics) has begun to be used proactively for the main structure of Boeing 787 and other civil aviation aircraft as well. In addition, the use of CFRP has been expanded also to railway cars (more specifically, bullet trains' front ends and covers). These trends have provided an impetus to its use for bogies as well.

To date, railway car bogies have been recognized as running gear, i.e., a critical component, and therefore have been designed with an emphasis on operation results for several decades. Based on the aforementioned backdrop, however, we had considered fundamental changes in the bogie structure and review of applicable materials, and consequently accelerated the development of efWING, a weight-saving bogie with improved running safety.

2 Course of events that led to development

(1) Development of a CFRP leaf spring

Since 2011, we have been advancing the development of a CFRP leaf spring and have developed its design based on the load conditions for conventional lines in Japan as a three-point bending spring element, which is suspended at its both ends and subjected to a vertical load at its center. In this connection, a radius arm type for primary suspension (which has been service-proven) has been adopted to suspend the axle box in longitudinal and lateral directions and is available for the purpose of eliminating the need to incorporate a major developed element in this part

† The weight of cars has been reduced by approximately 1 ton per car to reduce running costs and CO_2 emissions. Noise and vibration are also minimized.

to realize configuration that would be easily accepted in the commercialization phase.

First, a static load test was conducted to verify the strength and rigidity of the spring alone. As a result, it was proven that the spring had the predetermined spring constant and that it had static strength with an adequate safety factor with respect to the full load condition, i.e., the maximum load applied during actual service. In addition, a railway car materials combustion test was conducted to check for flame retardancy, which the aforementioned CFRP leaf spring must have as a material applied for railway cars. As a result, it was revealed that the CFRP leaf spring was incombustible.

(2) Prototyping

A narrow gauge bolsterless bogie for use on conventional lines equipped with the aforementioned springs was prototyped. An assessment was conducted on the bogie using a rotary tester owned by Kawasaki with regard to the bogie's essential running performance. As a result, it was confirmed that the bogie was able to run without hunting even though the push/pull load was applied to the bogie up to 200 km/h, which sufficiently exceeds the running speed of commuter train.

In May 2012, the second prototype bogie, which had been fabricated in view of an actual running test, was completed. As the second prototype, a standard gauge bogie with bolster was adopted in view of an actual running test. Following the completion, a fatigue test was conducted on the leaf spring in parallel with a static load test and a rotation test for the bogie. As a result, it was confirmed that the second prototype had such performance, strength and durability that it was available for a test run.

Moreover, a bogie equalization test was conducted prior to the actual running test. This bogie equalization test was based on the unforgiving U.S. specification/standard, which requires that if any one of the wheels in one bogie becomes depressed or rises due to track irregularities, the vertical load between the wheel and the rail (wheel load) should not decrease. Figure 1 shows the results of this test. Conventional bogies have been designed allowing for little margin with respect to the limit values for conventional lines, as shown in Fig. 1. With regard to efWING, on the other hand, there was substantial margin with the amount of decrease of wheel load not more than 50%, compared with conventional bogies. In other words, it can be interpreted that the ability of efWING's wheels to track rails was two times that of conventional bogies. Consequently, it could be confirmed that efWING had excellent performance in terms of running safety. This is because the CFRP leaf springs balanced the wheel load on the front wheels with the wheel load on the rear wheels like a seesaw with the spring's central part acting as a fulcrum. It can be said that this high bogie equalization performance is a major feature of efWING.

(3) Running test

In June 2012, a running test was conducted at Transportation Technology Center, Inc. (TTCI) in Colorado in the United States (a subsidiary of the Association of American Railroads). This test was conducted using a four-car train: the first car was a traction locomotive; the second car was a gauging car loaded with measuring instruments; the third car was a passenger car with conventional bogies to compare with efWING; the fourth car was a passenger

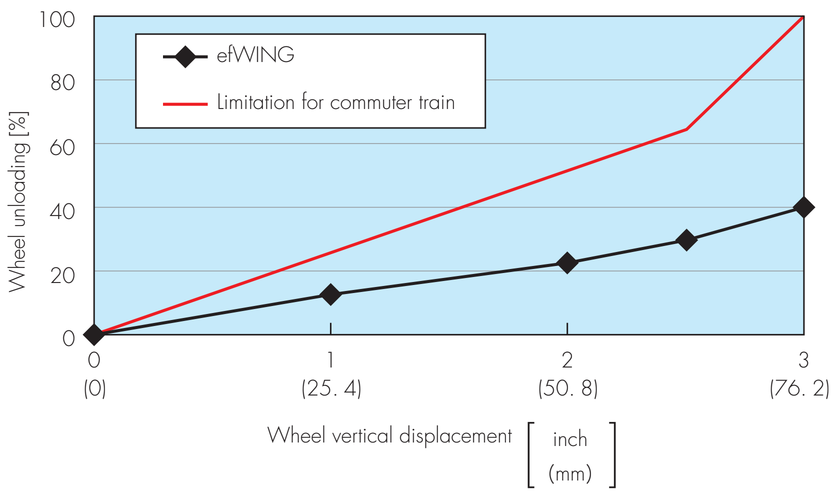


Fig. 1 Wheel unloading requirement

Fig. 2 Running test car

car with efWING, instead of conventional bogies (Fig. 2).

The running test was conducted for a total of 20 days, achieving a car mileage of 4,469 km. Of the multiple loop tracks located in TTCI's site, the longest high-speed track has a total circumference of 21.7 km. With the maximum speed set at 160 km/h. i.e., the critical speed of hunting for the locomotive, running was repeated. In addition, test data on sections with a 145-meter radius, high degree curve and "sections with a figure 8" or other high degree switches were also accumulated. Moreover, all types of sections with extraordinary track irregularities, i.e., pitch and bounce sections, where vertical irregularities of the left and right rails are in phase with each other, twist and roll sections, where such irregularities are in reverse phase with each other, and yaw and sway sections, where lateral irregularities of both rails are in phase with each other, were run to ascertain the dynamic properties, including strain, acceleration and wheel load histories.

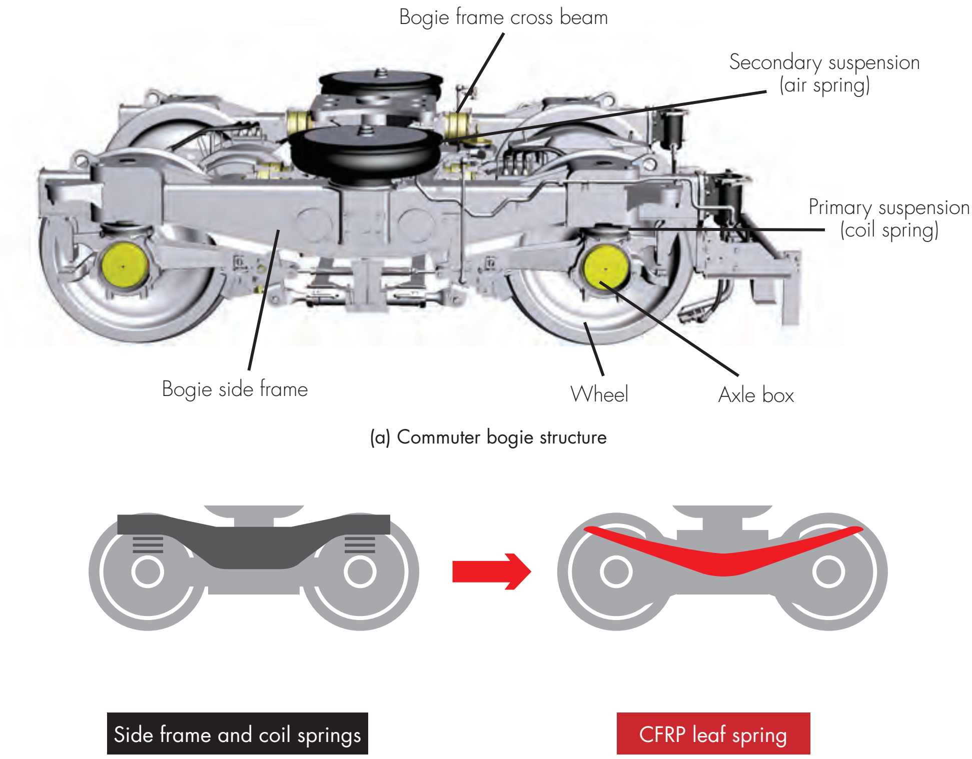
efWING met the requirements regarding the running safety of railway cars, as stipulated by FTA (Federal Transit Administration), throughout the speed range of 48–160 km/h. Consequently, it was proven to be able to run safely.

3 Basic structure

Generally, a railway car bogie consists of main structure components and equipment necessary for running. The main structure components include four axle boxes, in which journal bearings are housed, an axle box suspension structures and a bogie frame structure. The equipment necessary for running includes motors, gears, brakes and suspensions.

efWING is a bogie that was devised as a result of fundamentally reviewing conventional bogies' functions without being obsessed with the conventional bogie structure. The concept of efWING, focusing on the carbody load transmission path in conventional bogies as illustrated in Fig. 3 (i.e., carbody → secondary suspension (air springs) → bogie frame cross beams (transom) → bogie frame sidebars (side frames) → primary suspension (coil springs or the like) → axle boxes, axles and wheels → rails), is to replace the bogie frame sidebars and primary suspension, out of the components constituting the aforementioned path, with a pair of CFRP leaf springs to achieve structural simplification and weight reductions.

Due to such replacement, the frame structure could be entirely changed to eliminate the need for sidebars. In the context of comparing the bogie that underwent a TTCI test with a conventional bogie for use in North America, the bogie mentioned first has achieved approximately 40% of reduction in bogie frame weight with respect to the conventional bogie, which is equivalent to a weight reduction of 900 kg per car. In addition, efWING has achieved simple assembly structure as well. The leaf springs are simply placed on the axle boxes without being fastened to the axle boxes or the bogie frame cross beams with bolts, pins or the like, and the bogie frame cross beams are also mounted simply through the fulcrum at the center of the leaf springs.



(a) Commuter bogie structure

(b) New-generation bogie structure

Fig. 3 Design concept

4 Design pursuit

Since the beginning of the development of efWING, we have pursued design that allows the presence of the bogie to be demonstrated keeping it in mind that unprecedented coloring should be adopted to make the bogie impressive. To date, only carbodies have drawn attention. However, the bow-like spring taking advantage of CFRP's performance led the way to the creation of a bogie that has innovative appearance as well. We applied for the Good Design Award, which we had long hoped to receive, and won a gold award in 2013. On that occasion, we received comments from the reviewers, including the following—"I would like to highly appreciate the creation of a high-performance bogie with functional beauty from new material technologies and structural development of which Japan is proud." This is an outstanding achievement in that we received an award related to bogie design for the first time.

5 Expansion of domestic applications

Kumamoto Electric Railway Co., Ltd. had replaced two conventional bogies used for its Series 6000 EMU with efWING bogies and brought the EMU into commercial operation on March 14, 2014 (Fig. 4).

Moreover, in March 2015, Shikoku Railway Company conducted a test on efWING's applicability to car commercially operated in Japan. The test results are shown below.

Fig. 4 Series 6000 EMU operated by Kumamoto Electric Railway Co., Ltd.

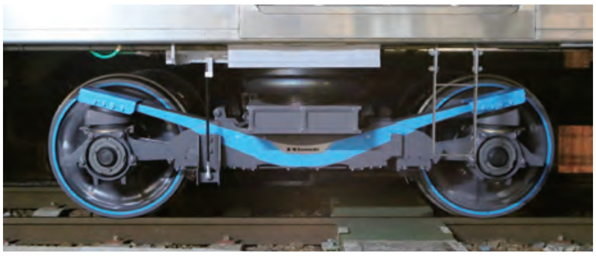
(1) Tested cars

A running test was conducted using a 121 Series DC suburban EMU equipped with test bogies as shown in Fig. 5 (a).

With the Tadotsu–Takihama section (66.7 km) on the Yosan Line set as the test section, a running test was conducted at speeds of up to 100 km/h for five days.

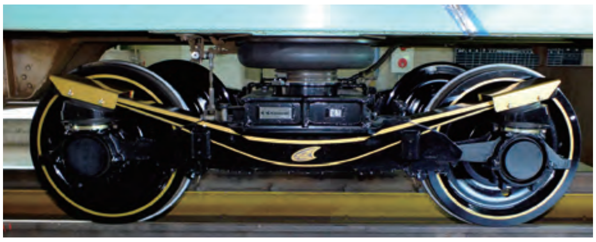
(2) Running safety

Running safety was assessed using three evaluation items: derailment coefficient, decrease ratio of wheel load and lateral force. It was confirmed that the efWING test bogie met the guidelines for all items. In addition, running safety was assessed also by maximum carbody floor vibration acceleration. Assessment guidelines were set to



(a) Bogie for Series 121 operated by Shikoku Railway Company

(b) Bogie for Series 817 operated by Kyushu Railway Company



(c) Bogie for Series 7000 operated by Nishi-Nippon Railroad Co., Ltd.

(d) Bogie for Series 7200 operated by Shikoku Railway Company

Fig. 5 Bogies used for running tests conducted by railway companies

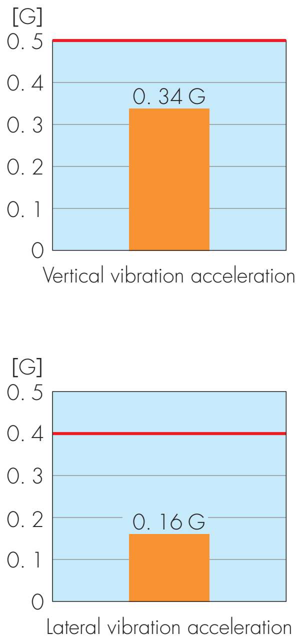


Fig. 6 Comparison of remarkably high values of carbody floor vibration acceleration (efWING test bogie)

0.5 G and 0.4 G for vertical vibration acceleration and lateral vibration acceleration, respectively. It can be understood from Fig. 6 that both vertical and lateral vibration accelerations met the respective applicable guidelines.

6 Expansion of applicability to various cars

Following the commencement of the aforementioned commercial operation, Kumamoto Electric Railway Co., Ltd. brought into commercial operation two Series 01 cars that have efWING bogies on March 16, 2015 and two more Series 01 cars that have efWING bogies on March 1, 2016.

Following the aforementioned running test conducted by Shikoku Railway Company, other running tests were conducted by Kyushu Railway Company and Nishi-Nippon Railroad Co., Ltd. in April 2015 and October 2015, respectively. The efWING bogies as shown in Figs. 5(b) and 5(c), both of which had replaced conventional bogies, were used for the earlier and later running tests, respectively.

Moreover, Shikoku Railway Company had planned to renew the major equipment for 121 Series DC suburban EMUs and has brought into commercial operation 7200 Series with efWING as shown in Fig. 5(d) in June 2016.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Conclusion

Running safety and ride quality of efWING have already been verified and commercial operation is being started. In the future, we will make further technological improvements and endeavor to develop efWING into an innovative technology and disseminate it to railway operators in Japan as well as in other countries around the world.

We hereby express deep gratitude to everyone who has continued cooperating with us until efWING became available for commercial operation.

Design Development to Improve Customer Satisfaction

To make a design that obtains high customer satisfaction, it is important to make the design attractive to all people and at the same time ensure high standards of safety and operability.

To provide the customer with a detailed design idea, we have employed a design process that minimizes reworking by using affective engineering and digital mockups.

Introduction

Although the market for railway systems in Japan has leveled off recently, demands for new cars are steady, such as replacement of existing cars and introduction of limited express trains.

Amid passengers' growing needs for attractive car designs these days, railway companies (our customers) are increasing their requirements for unique car designs. On the other hand, these designs also have to ensure high-quality manufacturing, safety, and operability. The challenging task is to design cars that meet both the required level of appearance and performance. We have won bids for our high evaluations in total assessment of bid proposals including not only prices but also designs, technologies, and quality—e.g., the new limited express train 500 Series (Fig. 1) of Tobu Railway Co., Ltd. (hereafter referred to as Tobu Railway), and the new commuter train

Fig. 1 Exterior of Tobu Railway's new limited express train 500 Series

Fig. 2 Exterior of Seibu Railway's new commuter train 40000 Series

40000 Series (Fig. 2) of Seibu Railway Co., Ltd. (hereafter referred to as Seibu Railway). They are large private railway companies in the Kanto region. We employed the new design process in these cars' designs and in their sales activities.

1 Background

In the conventional design process, detailed studies are made by using two-dimensional drawings, and three-dimensional checks are conducted only after making mockups and in the last stage of designing and the first actual car. In this process, the design often differs from the customer's expectation, which leads to reworking the design.

To respond efficiently to the customer's requests, we have implemented affective engineering and digital mockups as described below.

By employing effective engineering methods to scientifically verify our designer's multiple design proposals based on the customer's design concept, we made more specific perspective drawings. Consequently, we developed a new design process (Fig. 3) that provides a realistic car concept at an early stage of the design process, in which the customer can check 3D (three-dimensional) digital mockups of VR (virtual reality) images made from 3D data.

Fig. 3 Design workflow that incorporates the customer's requests

2 Affective engineering applied to car designs

Affective engineering is a technical field that makes objective data (visualization) out of physically unseen human information such as feelings, perception, mental images, emotions, and sense of values.

Generally, many people are involved in decision-making processes for assessing the design, and individuals' subjective ideas tend to affect the results. Consequently, discrepancies are often seen between the detail design and the concept design and oftentimes much time elapses before deciding on the final design.

Affective engineering, which objectively detects human feelings, provides persuasive evidence that the final design satisfy its initial concept. Kawasaki introduced affective engineering in designing motorcycles at first, and then in 2008 we started using it in projects for developing cars for the Japanese domestic market.

Seibu Railway's new commuter train 40000 Series (hereafter referred to as 40000 Series) shown in Fig. 2 aims at establishing a new standard commuter train, on which special areas called "Partner Zones" are set up to offer comfortable spaces for passengers who use wheelchairs or strollers.

At the technical proposal for the bid, we presented a new interior design that used our past research results in the field of affective engineering, which was highly evaluated.

The exterior design of the car head is an important factor for the customer's corporate brand, and it attracts passengers' interest every time they ride the train. The next paragraph starts to explain how we practically applied affective engineering to designing the head part of the 40000 Series.

First, our designers presented multiple design proposals based on the customer's concept that showed graceful shapes with some colors of existing cars. Next, many of the people involved, including our customer, shared their impressions regarding the exterior shapes and colors of each design by completing evaluation sheets. MDS (multidimensional scaling), a psychometric method, was used to compare the impressions obtained from these evaluation sheets such as "warm," "cold," and "splendid" with "gentle" and "advanced" that were conceptual key words of this project, and then the consistency of these exterior designs were checked on a 3D map (Fig. 4). Model D, for example, is visualized to show it is an exterior design that gives an impression of flowery and bright appearance. These processes were repeated multiple times to fine-tune the designs. As a result, a final satisfactory design that met the original concept was selected with confidence and speedily.

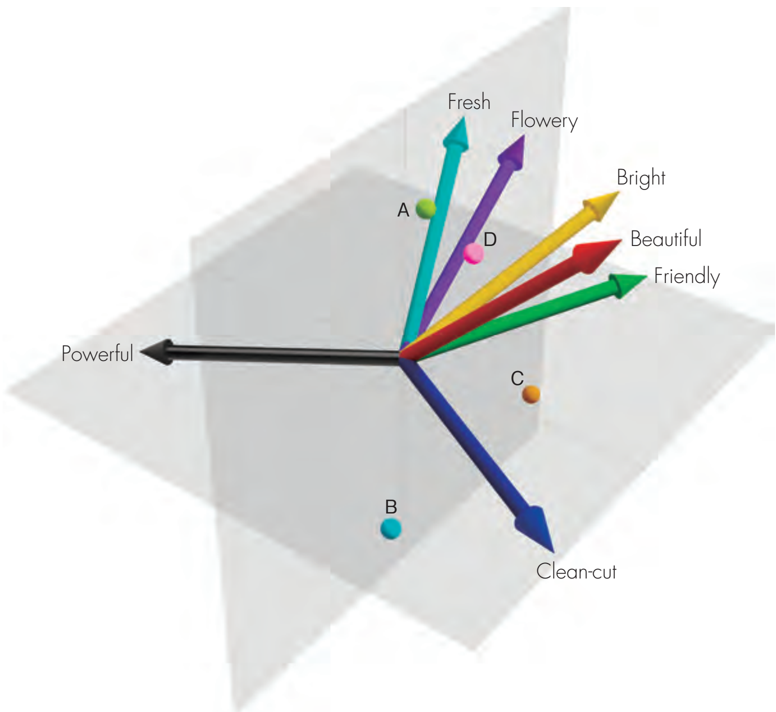

Fig. 4 3D map created by MDS (multidimensional scaling)

3 Digital mockups used in design processes

To realize the new design process shown in Fig. 3, we invented a method that evaluates human factors from both subjective and objective perspectives by introducing digital mockups that use VR and human engineering (3D human simulator). The VR technology creates a virtual space on a computer and provides users' senses with appropriate information to allow them to experience things in the space as if they were there although they do not physically exist in reality.

Meanwhile, human engineering puts up 3D human models of various shapes in a virtual space on a computer. They can be moved freely to check operability of a machine numerically. Combining these technologies enables human factors to be evaluated from both subjective and objective perspectives.

By using digital mockups, designers can check their designs and customers can check the design specifically by experiencing it before the product is constructed. At this stage of designing, digital mockups allow flexible design changes making it easy to reflect the customer's requests on the car design. Figure 5 shows scenes of using digital mockups.

Tobu Railway's new limited express train 500 Series (hereafter referred to as 500 Series) shown in Fig. 1 has a concept of providing quick-deliverability and comfort in various operating conditions. This is realized by forming the 500 Series consisting of two three-car unit trains connected together (for a total of six cars), which can operate as one train of six cars or be separated along the route and operate as two trains of three cars each.

The exterior design gave a car head that had never been used for past limited express trains and this raised an issue about securing an adequate viewing area for the

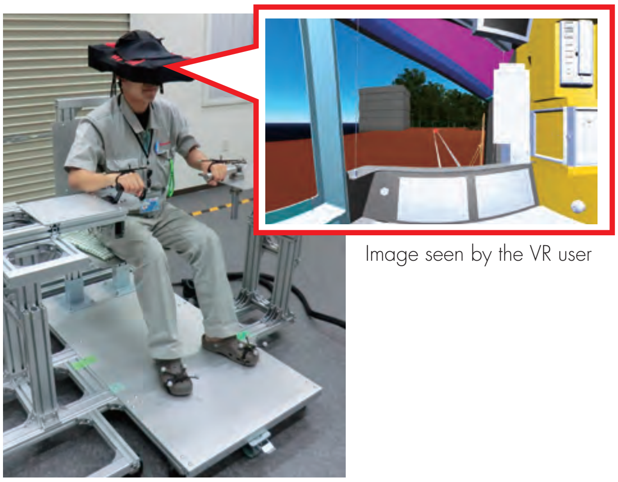

Image seen by the VR user

VR user

(a) Virtual reality

(b) 3D human simulator

Fig. 5 Design review with digital mockups driver. Conventionally, verification has been conducted by making a mockup after reviewing two-dimensional drawings. For the 500 Series, VR was used in checking the visibility through 3D digital mockups and the head shape was optimized, and then by simulating the 500 Series with an existing car, a final design was validated (Fig. 6).

VR was also used for the basic design of Seibu Railway's 40000 Series. For example, 3D data were created based on the perspective drawing of Partner Zone in Fig. 7(a), and a VR user moved a real stroller to check the comfortability inside the car as shown in Fig. 7(b).

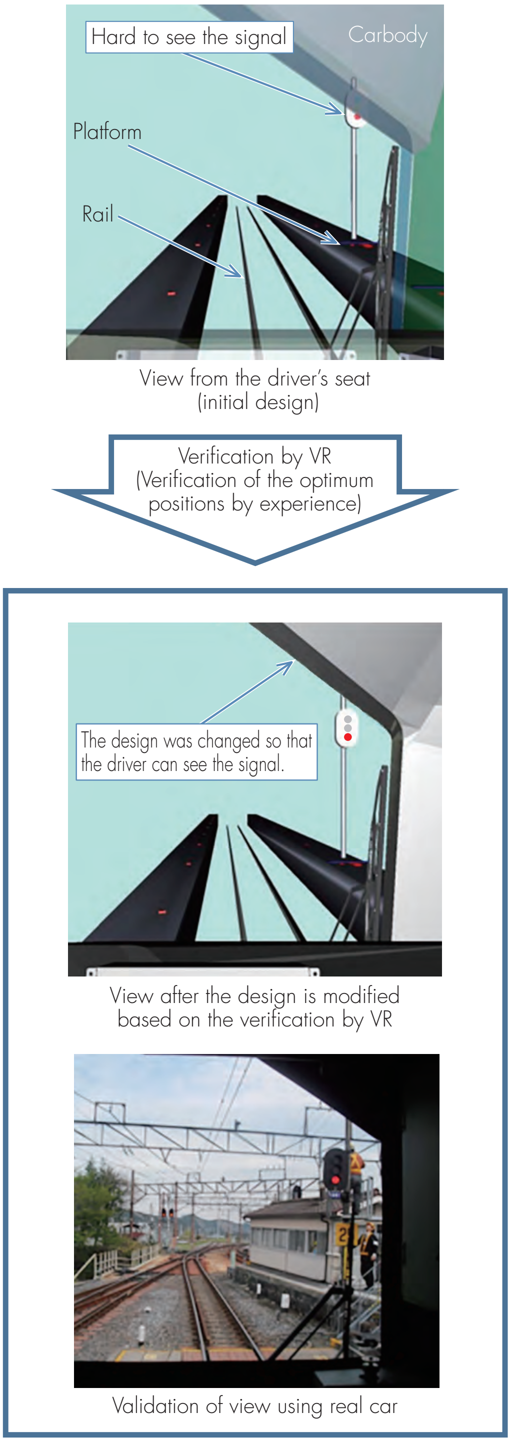

Fig. 6 Design verification by VR (Tobu 500 Series)

(a) Image of Partner Zone

(b) Scene of verification by VR

Fig. 7 Design verification by VR for Partner Zone (Seibu 40000 Series)

Conclusion

Applying affective engineering and digital mockups to car designs in the early stages of the design process helped us win bids for the new limited express train 500 Series from Tobu Railway and the new commuter train 40000 Series from Seibu Railway.

The bid conditions required by these customers included not only prices but also design and technology evaluations. We made front-loading proposals focused on creating designs that satisfy customers.

We expect an increase in designs requiring originality going forward. We will use this newly developed design process to design cars that will assure that our customers are highly satisfied.

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Original and Innovative Onboard Systems to Address Rolling Stock Needs

There is increasing demand for the basic requirements of safety, stable operation and comfort that vehicle is expected to provide, as well as for the reduction of costs required to maintain vehicle and tracks. To meet such demand, Kawasaki is developing various onboard systems and is moving forward to put them into practical application. These include an active suspension system that will improve passenger comfort, a Bogie Instability Detection System (BIDS) that will help ensure safe and stable operation and efficient bogie maintenance, and a track monitoring system that will help cut track maintenance costs.

Introduction

As a means to realize safe and secure mass transport with low cost, railways have been advancing in terms of the following aspects: actively introducing railway networks in emerging nations, and upgrading quick-deliverability, comfort and other convenience factors in nations with well-developed railway networks such as Western countries and Japan.

1 Background

Amid intensification of competition with airplanes and other means of transportation, railway companies have further improved convenience and accelerated initiatives to reduce lifecycle costs.

With growing demands of basic requirements for vehicle to provide safe running, ensuring stable operation and a more comfortable ride as well as requirements for railway companies to cut costs through more efficient vehicle and track maintenance, Kawasaki has supplied onboard systems meeting such demands.

2 New onboard systems

Kawasaki has developed onboard systems, which are in practical use, including the following: active suspension system that improves passenger comfort, Bogie Instability Detection System (BIDS) that helps ensure safe and stable operation and efficient bogie maintenance, and a track monitoring system that helps reduce track maintenance costs.

3 Active suspension system that improves passenger comfort

(1) Overview

With vehicle speeds increasing, ensuring passenger comfort has been challenging in recent years, and as one of the technologies to cope with this challenge, the vibration control technology to control vehicle vibration has become vital. Its overview is shown below.

(i) System configuration of vehicle

Causes of vehicle vibration include transmission of vibration of a bogie excited by track irregularity to the vehicle's body and direct excitation of the vehicle's body due to aerodynamic force from traveling at high speeds. Attributed to faster vehicle, difficulty in controlling vibrations from two different sources only through the tuning of springs or dampers on a vehicle has arisen.

(ii) System configuration of active suspension system

To address the problem mentioned above, an active suspension system has been developed to detect vehicle vibration using sensors and to generate some force to cancel out vehicle vibration using an actuator mounted between the bogie and vehicle body, and has been adopted mainly in Shinkansen (bullet train) and other high-speed vehicle (Fig. 1).

(2) Initiatives carried out at Kawasaki

The development status in Kawasaki is described below.

(i) Development and performance evaluation of active suspension system

Taking into account the recent growing demand for

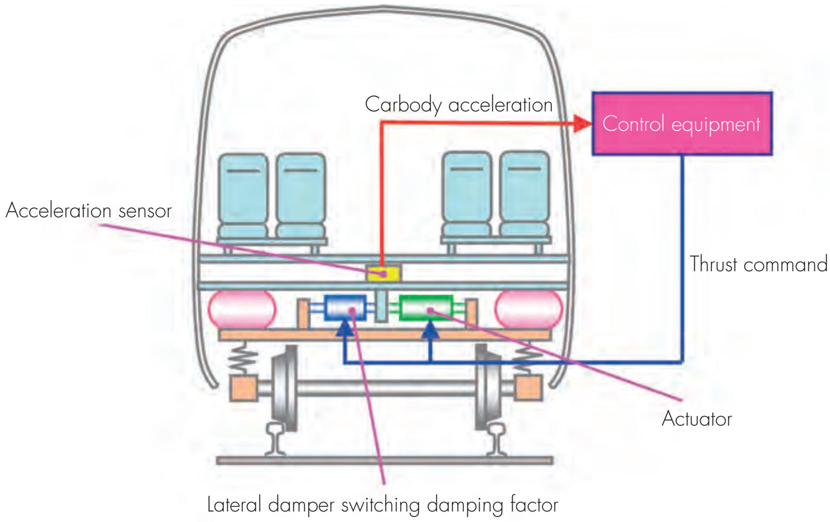


Fig. 1 System configuration of active suspension system

reduction in air consumption, in particular, and improvement in actuator response, we have developed an active suspension system using electric actuators, replacing conventional pneumatic actuators that are primarily used. The results of performance tests carried out so far using bench test equipment or test vehicle have proved its high vibration control performance (Fig. 2).

(ii) Development of new actuator

Recently, from the viewpoint of better passenger service, there has been an increasing demand for active suspension systems not only for Shinkansen and other high-speed vehicle, but also for limited express trains on conventional lines and other mid-speed vehicle. Further downsizing of an actuator is required for mid-speed vehicle, and to meet such requirements, Kawasaki has newly developed a small, lightweight actuator.

Use of a highly accurate ball screw in the drive unit enables efficient power transmission, and as a result, in addition to downsizing and weight reduction, adequate high output performance has been achieved with an excellent energy-saving feature (Fig. 3).

Mounted on GCT (gauge change train) new test vehicle, which can run on tracks of two different rail gauges, the system has proven it has good vibration control performance in running tests on both Shinkansen and conventional railway tracks.

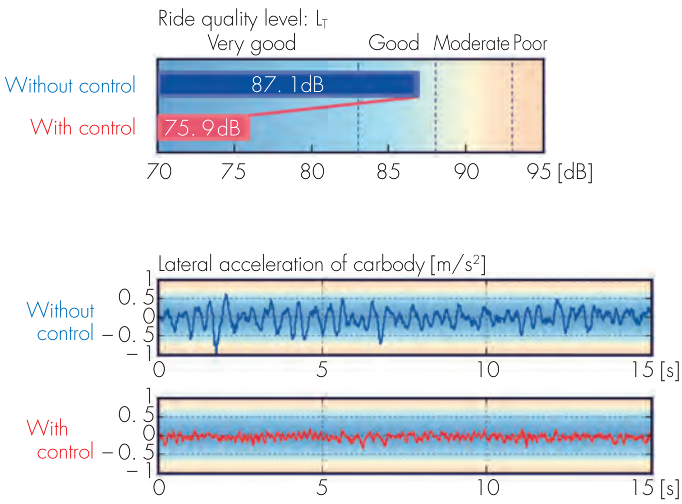


Fig. 2 Running test results

	For high-speed vehicle	For mid-speed vehicle
Type	Ball screw drive	
Weight [kg]	40	32
Installation length [mm]	470	462
Thrust [N]	Max. 8,000	Max. 6,000
Application target	GCT new test vehicle	–

Fig. 3 New actuator for active suspension system

4 Bogie Instability Detection System, BIDS, that realizes safe and stable running

(1) Overview

Bogies are one of the most important components composing vehicle, and are designed with various considerations to achieve safe and stable running. However, the following matters cannot be avoided just by considering them in the design stage, and require other measures.

- Degradation of supporting component, wheel abrasion or other relevant factors may cause an unstable phenomenon called hunting, and leaving such a phenomenon unattended poses a higher risk of derailment.
- Trouble with axle bearing, gear unit, coupling joint or other components in drive transmission system hampers vehicle's stable operation.

Aiming at avoiding both above cases, Kawasaki has developed BIDS (Bogie Instability Detection System), a system to monitor status of a bogie by sensing vibrations and temperatures, and has expanded its use mainly in overseas high-speed vehicle.

(2) System configuration

As shown in Fig. 4, BIDS measures lateral vibration using the acceleration sensor mounted on a bogie frame, and detects indication of hunting at the monitoring unit in accordance with level and continuity of vibration. Detection results are immediately notified to the driver so as to safely decelerate the vehicle. Drive transmission systems are monitored mainly by the temperature switches, and abnormal rises in temperature are directly notified to the driver's cab.

(3) Characteristics

(i) Highly sensitive of acceleration sensor hunting detection performance

Extraction of the hunting frequency component determined based on bogie design specifications and running speed allows detection of hunting in the early stages. Additionally, the system can adapt to the higher speed of vehicle.

(ii) Highly reliable in poor environments

Even in such severe environments as vibration, shock, intensive surge and noise, the system maintains its performance without any trouble, and is free from periodical calibration and maintenance.

(4) Applications

(i) BIDS for high-speed vehicle

We have started delivery to Taiwan High Speed Rail Corporation and China South Locomotive and Rolling Stock Industry Group Corporation. The cumulative shipments have exceeded 5,100 sets. Also, to supply the system for unified standard vehicle, which is under development by China Railway Rolling Stock Corporation, a new system has been newly developed to adapt to world-standard vehicle network of MVB (Multifunction Vehicle Bus) and Ethernet

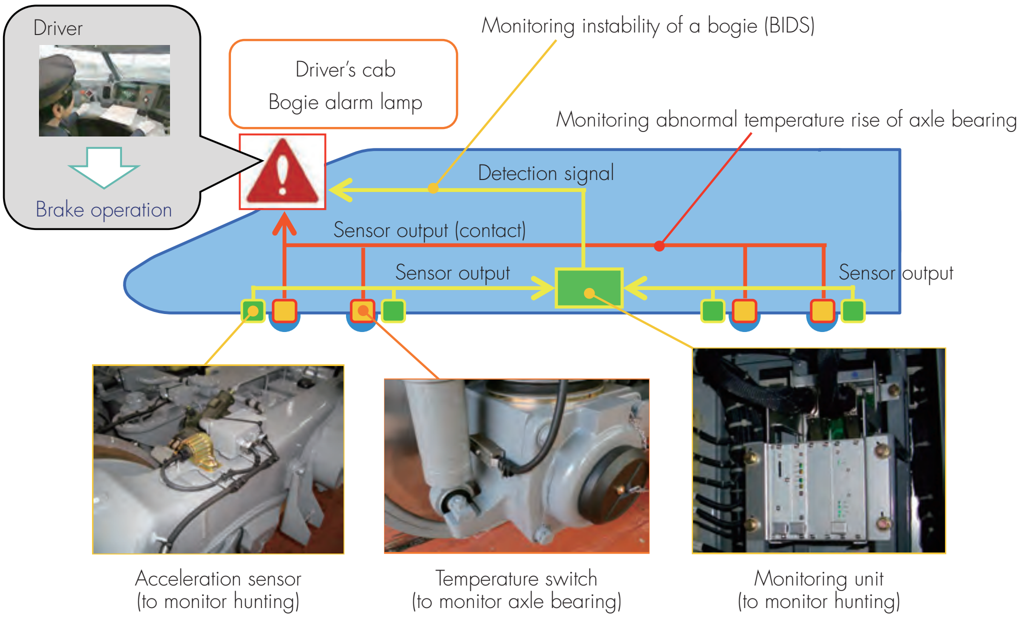


Fig. 4 System configuration of BIDS

that is expected to dominate in the future, and as a result, substantial functional improvements have been achieved, leaving the body dimensions and shape as they stand.

(ii) BIDS for efWING

A new monitoring system has been developed to be mounted on the next-generation bogie efWING (Fig. 5 (a)) that has adopted CFRP (carbon-fiber-reinforced polymer) in the main structure of the bogie frame. Unlike the conventional type, this system is characterized by the fact that the monitoring unit is directly mounted onto the bogie. At present, continuous evaluation is being performed on durability and reliability using a system mounted onto actual vehicle.

① Bogie-mounted monitoring unit (Fig. 5 (b))

It was verified that, even in an extremely severe environment on a bogie, the unit works properly and maintains vibration/shock Category 2, IP66 for dust/water resistance, and the other performances shown in Table 1.

② Health monitoring sensor for CFRP leaf spring

Employing the in-house-developed sensing method using the conductivity of CFRP, the system allows continuous monitoring of not only vibration and temperature but also the internal state of the CFRP leaf spring.

③ Remote monitoring and state diagnosis

Transmitting the bogie's behavior data during running as needed via a wireless communication line to our data center, the system allows abnormalities in the bogie's behavior to be analyzed and diagnosed.

(5) Higher level of maintenance efficiency led by condition monitoring

Kawasaki has built and operated the system with more monitoring items extended from conventional BIDSs, and has launched continuous collection of the bogie's behavior data. Along with sophistication of diagnostic technology based on the collected data, we are building a system for monitoring and diagnosing conditions (Fig. 6) at the bogie's component level through the active use of IoT (Internet of Things) technology, and are striving to achieve both safety and stable operation and maintaining bogies more efficiently.

(a) efWING

(b) Monitoring unit

Fig. 5 efWING and bogie-mounted monitoring unit

Table 1 Main specifications of bogie-mounted monitoring unit

Item	Specifications
Ambient temperature	−25°C to 70°C
General environment	IEC60571 (humidity and temperature, insulation resistance, etc.)
Electromagnetic compatibility	IEC62236-3-2 (surge on vehicle, noise, etc.)
Vibration/shock test	IEC61373 Category 2 (bogie-mounted equipment)
Dust resistance, water resistance	IP66 equivalent (water-resistant type, strong direct jet stream)
Number of measuring points	13 points
External interface	Power supply, running speed information line, LTE/3G transmission line

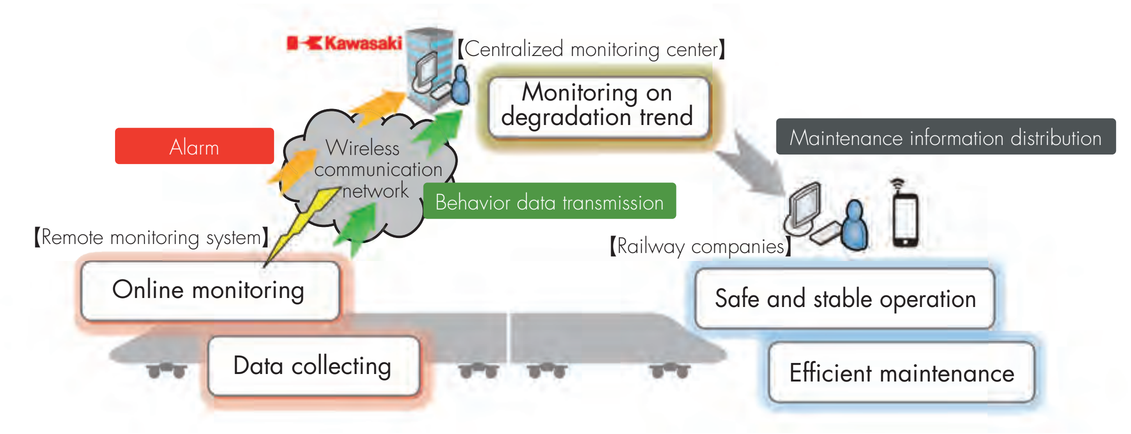


Fig. 6 Remote monitoring and diagnostic system

5 Track monitoring system that guarantees safety from tracks

(1) Overview

Track facility maintenance depends primarily on visual walking inspections, and for this reason, saving energy and automating track maintenance and inspection work has been an important issue for railway companies.

Kawasaki has developed a track monitoring system for East Japan Railway Company (JR-East) to meet the abovementioned demands. Following are the characteristics of this system:

① Recording running feature

Ten cameras mounted on the onboard equipment shown in the frontispiece photo enable the continuous recording of track images during traveling.

② Automatic detection feature

Using ground equipment, the system allows automatic detection of abnormalities in the rail fastener and fish plate through image processing.

③ Compact housing size

In terms of size, the onboard equipment can be installed under a floor of vehicle and be mounted onto commercial vehicle. Using such an advantage, the system allows the latest track images to be obtained with high frequency during routine commercial driving.

(2) System configuration

Figure 7 shows the system configuration of the onboard equipment, and the information below describes features of the configuration.

・The onboard equipment consists of the following items:

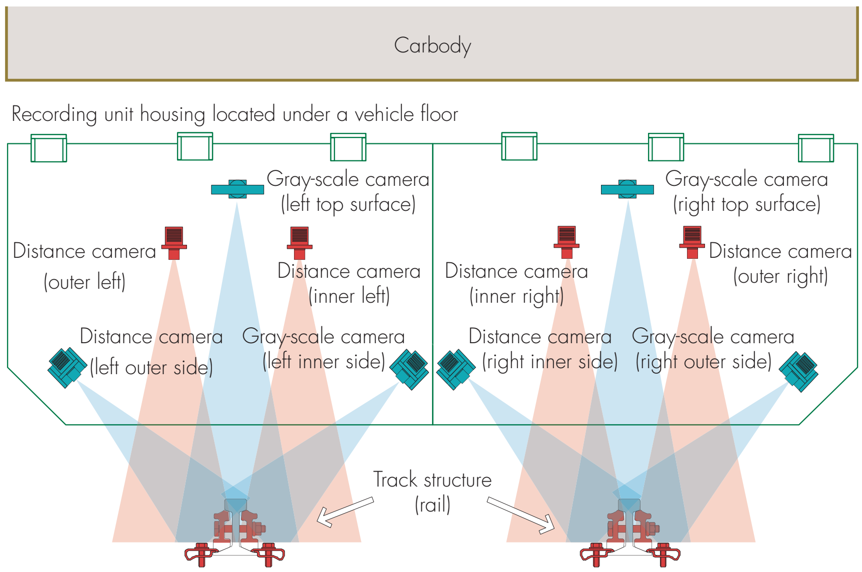
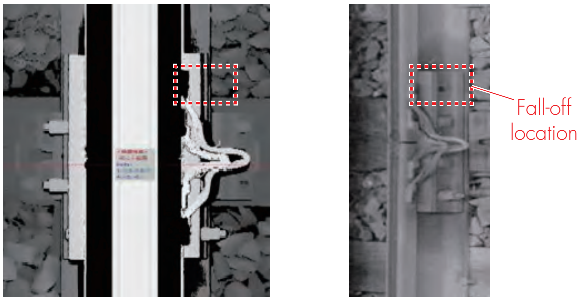


Fig. 7 System configuration of onboard equipment



(a) Distance camera (b) Gray-scale camera (side view)

Fig. 8 Detection result of fish bolt defect

six gray-scale cameras that capture gray-scale images of track surfaces for visual monitoring, four distance cameras that capture three-dimensional form for automatic detection of falling-off of rail fastener and fish bolt, a controller that controls the abovementioned cameras, and a data recording unit.

- Synchronizing with the pulse output by the vehicle mounted velocity sensor at a constant distance, the respective cameras carry out shooting.
- Captured track images are stored in the data recording unit and periodically extracted.
- Using the ground equipment in an office, image processing and detection processing are done offline.

Automatically detectable items include falling off of diverse kinds of rail fasteners, fish plates and fish bolts. Figure 8 shows the location where fall-off was automatically detected through detection processing.

(3) Applications

Since fiscal 2013, the system has been mounted on commercial vehicle on the Tokyo metropolitan area route run by JR-East, and the one-year trial operation was performed.

Mass production started in fiscal 2014, and the said system has also been applied in the Chuo Line and the Yamanote Line, and started its service in fiscal 2015. Going forward, we plan to mount the system for the other railway routes in sequence.

Conclusion

We assume that the onboard systems introduced this time can contribute to a safer and more comfortable ride and stable rolling stock operation as well as reducing maintenance costs.

It was essential to have guidance and cooperation from JR-East, Kumamoto Electric Railway Co., Ltd. and other railway operators for developing the respective onboard systems. We deeply acknowledge all relevant parties with our sincere gratitude.

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Series E7/W7 Shinkansen trains for the Hokuriku Shinkansen Line

In spring 2015, the operation of the Hokuriku Shinkansen bullet trains began between Nagano and Kanazawa using Series E7/W7 trains. The concept of these cars is the "The future with a Japanese sense of harmony": Japanese traditional beauty can be seen here and there and has been combined with advanced technologies to create new value. The cars' high performance allows them to cope with severe line conditions. Their functionality has been enhanced to improve customer services and reduce the amount of electricity consumed. We have manufactured and delivered five train sets to East Japan Railway Company and four sets to West Japan Railway Company.

Introduction

The Hokuriku Shinkansen line is a bullet train line that connects Tokyo to Osaka via the Joshinetsu and Hokuriku areas. The operation between Nagano and Kanazawa started in the spring of 2015. Series E7/W7, jointly developed by East Japan Railway Company and West Japan Railway Company, was introduced as the Hokuriku Shinkansen trains.

1 Train formation

A single train set consists of a total of five units (12 cars): Three-car units including the lead cars and two-car units that consist of only middle cars (Fig. 1). Cars one to ten are Ordinary cars, Car 11 is a Green car, and Car 12 is a GranClass car.

New train names Kagayaki, Hakutaka, and Tsurugi are used in addition to the existing name Asama. The fastest

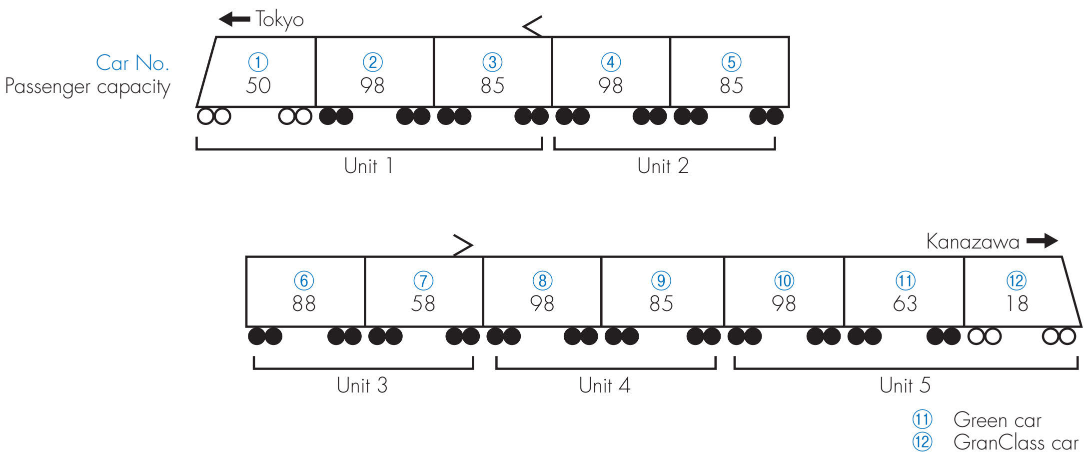

Fig. 1 Train formation

train, Kagayaki, runs from Tokyo to Kanazawa (approximately 450 km) in about two and half hours (maximum speed: 260 km/h).

2 Features

(1) Design

Japanese people have established a culture in which Japanese style is being valued over a long period of time. We proposed and developed the design concept “The future with a Japanese sense of harmony” because we hoped that the Hokuriku Shinkansen trains would shoulder and tow the future for which such value is further developed.

(i) Exterior design

The appearance (shape) and colors were designed and developed under the theme “combination of tradition and future.” The smooth and flowing One-motion line (simple streamline front-end) represents a sense of speed giving it a tough and masculine look while maintaining environmental performance, for example, performance for reducing micro-pressure waves that are generated when a train passes through a tunnel.

The body colors of blue, copper, and white represent the combination of tradition and an image of the future. Blue represents the sky spread over the Hokuriku Shinkansen and copper is from copperware and inlaid work (Japanese traditional handicrafts) while white represents dignity and tranquility seen in Japan (Fig. 2).

Fig. 2 Lead car

(ii) Interior design

GranClass cars were designed under the theme of "Harmony of passengers and space." Green cars were designed under the "Harmony of style beauty" and Ordinary cars were under "Harmony of color." They provide spaces in which much Japanese traditional beauty is harmonized (Figs. 3 and 4).

In addition, the vestibules of GranClass cars have red decoration plates with a motif of Japan's four seasons (Fig. 5).

(2) Facilities in trains

In order to improve customer services, all Western-style restrooms in the trains have warm-water washing features and all seats in Ordinary cars have electric outlets. In addition, only LED lights have been installed on the trains to reduce the amount of electricity consumed.

(3) Switching power supply frequencies

Power supply frequencies need to be switched in the middle of the Hokuriku Shinkansen route, so the trains have equipment that can operate at both 50 Hz and 60 Hz.

Fig. 3 GranClass cabin

Fig. 4 Green car cabin

Fig. 5 Vestibule of GranClass car

(4) Performance on steep slopes

The Hokuriku Shinkansen line has multiple steep slope sections (30 ‰ per mill). The trains have power output and braking performance that can handle such slopes.

(5) Ride quality

The trains have full-active suspension systems (systems that use actuators to generate vibration that cancel the side-to-side rocking motions to control vibration optimally) and semi-active suspension systems (systems that change the damping force of the dampers to control vibration optimally) to control side-to-side rocking motion in order to improve ride quality.

Conclusion

After the operation of the Hokuriku Shinkansen with these rains started, there continues to be a large number of passengers riding the train, so it has fulfilled its role as a major transport artery to Hokuriku.

In addition, the Japan Railfan Club gave a Blue Ribbon Award to the trains in 2015 because it valued the trains highly for their high level of safety and reliability secured even under severe line conditions and their excellent exterior and interior.

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8600 Series Limited Express DC EMU for Shikoku Railway Company

After the 8600 Series limited express DC EMUs were put into service in the Takamatsu–Matsuyama section in June 2014, the same EMUs were put into service in the Okayama/Takamatsu–Matsuyama section in March 2016.

These cars replaced the 2000 Series limited express diesel railcars that had operated as the Limited Express "Shiokaze" and "Ishizuchi," fulfilling the role of the limited express system for the Yosan Line. This is the first new production of limited express EMUs for the Shikoku Railway Company in 21 years. These cars incorporate state-of-the-art technologies, including a carbody tilting control system and LED room lights to reduce costs, save energy and help preserve the environment. Kawasaki manufactured and delivered four pre-volume production cars and 10 volume production cars.

Introduction

Shikoku Railway Company had been planning to reorganize the rolling stock for the limited express service in the electrified section of the Yosan Line, which connects Takamatsu with Matsuyama, to only consist of EMUs in order to reduce costs and replace the aging Series 2000 limited express diesel railcars.

In addition, the company wanted to have the new cars serve as a guide for the limited express cars to be introduced in the future. For example, the company demanded that amenities such as cabins and sanitary facilities reflect passenger needs so that the new cars would set the standard for the future limited express service on the Yosan Line along with the conventional 8000 Series EMUs.

1 Train formation

In order to ensure finely tuned car scheduling according to the passenger load status, each EMU is made up of two train sets or three train sets when a middle car is connected between the two drive cars.

Half of the front car cabin of a three-train set EMU bound for Matsuyama is used as a Green Seat cabin where the seats are arranged in rows consisting of two seats on one side and a single seat on the other.

Kawasaki undertook the production of all four of the pre-volume production cars (2 train sets × 2 train sets) and 10 volume production cars (2 train sets × 2 train sets plus 3 train sets × 2 train sets).

2 Features

(1) Design concept

The 8600 Series limited express DC EMU has been designed to be a futuristic limited express train with a nostalgic image based on a retrofuturism design concept. The cars were jointly designed by Shikoku Railway Company and our Design Division.

(2) Exterior design

The train's forcefulness and dynamism are expressed by the circular black face of the front end in the motif of a steam locomotive. The carbody is painted orange and green, conjuring images of gentle and beautiful nature in Shikoku – Kagawa and the warm climate in coastal areas of the Seto Inland Sea – Ehime. Also, the carbody has a streamlined shape, suggestive of the speed of a limited express train.

(3) Interior design

Well-lit and elegant cabin space that conjures up images of the future with orange and green accents that give the cabin interior a sense of natural warmth creating a sophisticated atmosphere for passengers to soak in (Figs. 1 and 2).

Fig. 1 Green car cabin

(a) Color representing Kagawa

(b) Color representing Ehime

Fig. 2 Ordinary car cabin

(4) Interior facilities

Cabins are equipped with electrical outlets for use with PCs or ohter devices on every seat, including those in ordinary cars, large baggage racks built according to the airline standard for carry-on baggage, emergency warning devices with communication functions, and so forth. Cabin lights use Kawasaki's straight tube LED lamps (Fig. 3), which save energy and reduce the need for maintenance.

LED downlights are also used on each deck and security cameras are located at each door.

Barrier-free arrangements include voice guidance devices and indication lamps interfaced with the opening and closing of side sliding doors.

(5) Comfort and ride quality

The air spring carbody tilting method developed by Kawasaki is used to improve the speed in a curve (Fig. 4). In this system the pressure in the outer air spring is increased in accordance with the tightness of each curve, which causes the carbody to tilt inward to cancel the centrifugal force.

Fig. 3 Self-powered straight tube LED lamp

† Compared with fluorescent lamps these lamps cut power consumption by 55% and weigh 75% less.
Conversion to LED limits waste since LED lamps are suitable for existing fluorescent lamp fixtures.

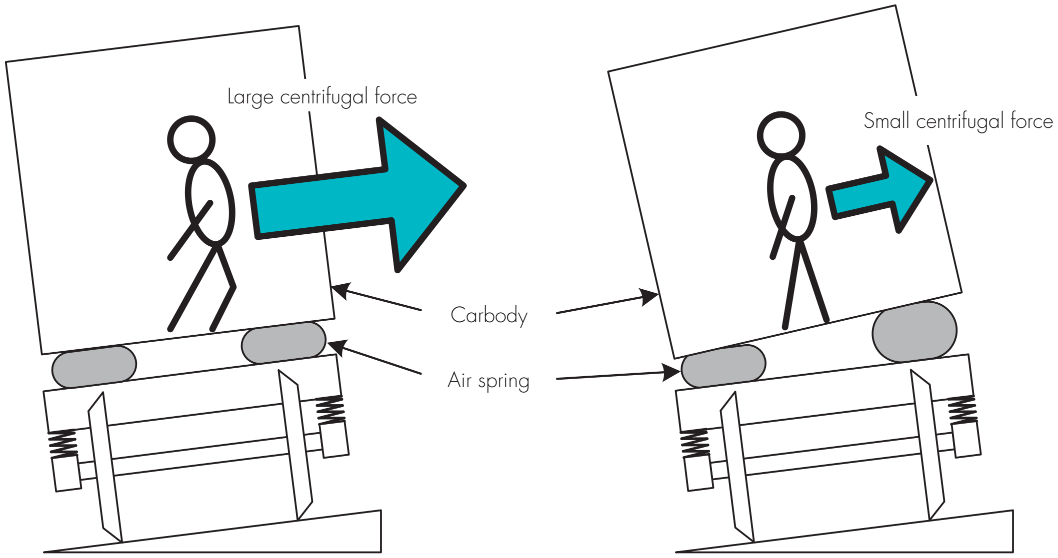

Fig. 4 Carbody tilting

(6) Bogies

Lightweight bolsterless bogies equipped with a carbody tilting system are used to ensure an operating speed of up to 130 km/h (maximum design speed: 140 km/h).

Conclusion

The order for the production of 8600 Series limited express DC EMUs was our first order from Shikoku Railway Company. We will endeavor to make the most of what we learned from the recent production of the EMUs so as to further increase orders from Shikoku Railway Company in the future.

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EMU for Taiwan Taoyuan International Airport Access MRT System

In February 2006, MKH Consortium (Marubeni Corporation, Kawasaki Heavy Industries, Ltd., and Hitachi, Ltd.) received an order from Bureau of High Speed Rail (BOHSR) of the Ministry of Transportation and Communications (MOTC) in the Republic of China (Taiwan). This order was for a contract to build a complete railway E&M system and depots for Taiwan Taoyuan International Airport Access MRT (TTYMRT).

Kawasaki manufactured and delivered 123 EMU (Electric Multiple Unit) cars; 68 Commuter cars and 55 Express cars. The Commuter and Express cars have different exterior and interior designs. However, they are identical in the major carbody structure and the operating performance, and a common design has been adopted as much as possible.

Introduction

Taiwan Taoyuan International Airport is the key portal to international communities. One important sign for being a developed country is her capability to provide airport passengers with a safe, convenient, comfortable and high quality transit service.

As one item of the government-funded "i-Taiwan 12 Projects," this airport link transit system Project will connect the Taoyuan International Airport with surrounding transportation hubs such as Taipei Main Station, High Speed Rail Taoyuan Station, etc. so that international airlines may tie closely to the local transportation web.

This Project can also stimulate prosperity along the route in coordination with the existing urban developments, to reach a more balanced city vs. countryside status.

1 Main specifications

Taiwan Taoyuan International Airport Access MRT System (TTYMRT) is a new MRT railway line that is 51.2 km long in total and connects Taipei Station (A1) and Huanbei Station (A21) in Zhongli District in Taoyuan City, via Taiwan Taoyuan International Airport. It is planned to be extended for two stations from Huanbei Station to Zhongli Station in the future.

On this railway, two types of trains will be operated: Commuter trains connecting between Taipei Station and Huanbei Station for local service, and Express trains

Table 1 Main specifications

Maximum number of passengers [persons] (Number of seats)	Commuter	DM car: 261 (44), M car: 278 (50)
	Express	DM car: 207 (48), M car: 216 (56)
Track gauge [mm]	1,435	
Maximum length [m]	DM/DMB car: 20.78, M car: 20.25	
Maximum width [m]	3.03	
Maximum car height [m]	3.763	
Floor height [m] (From top of rail)	1.133	
Distance between bogie centers [m]	13.5	
Current collection	750-VDC third-rail system	
Maximum service speed [km/h]	100	
Acceleration rate [m/s^2]	1.1	
Deceleration rate [m/s^2]	Service brake	1.0
	Emergency brake	1.3
Main circuit	IGBT VVVF inverter Three-phase squirrel-cage induction motor Continuous rated power 185 kW	
Brake system	Electro dynamic (regenerative and rheostatic) and friction brake with parking brake	
Auxiliary power system	380 VAC, 60 Hz, three-phase: 180 kVA 110 VAC, 60 Hz, single-phase: 2 kVA 110 VDC, 19 kW	
Battery	Nickel-cadmium alkaline battery, 130 Ah	
Communication system	Train radio equipment, Public address system, Passenger alarm equipment, Flight Information Display System, CCTV monitoring system	
ATC system	ATC, Event recorder	

connecting between Taipei Station and Taiwan Taoyuan International Airport for express service. Table 1 lists the main specifications of the cars.

2 Features

(1) Train configuration

Kawasaki delivered 17 sets of four-car Commuter trains (DM-M-M-DM) and 11 sets of five-car Express trains (DM-M-M-M-DMB), in total 123 cars. The car types are; DM cars (cars with a driving cab) and M cars (middle cars) for passengers, in addition, Express trains are accompanied with a DMB car (baggage car with a driving cab and baggage handling equipment), allowing passengers to check-in to their flight and check in their baggage at the in-town check-in counter, so that the passengers can travel with only carry-on baggage to the airport.

In order to travel continuous 4.92% steep gradient for 3.92 km on this line, all cars are equipped with driving motors.

Figure 1 shows the exterior view of Commuter DM car, Express DM car, and DMB car.

(2) Carbody

The car end underframe is made of low-alloy high-tensile steel (LART steel), while other portions are made

(a) Commuter DM car

(b) Express DM car

(c) Express DMB car

Fig. 1 Exterior view (DM/DMB car)

(a) Commuter - Interior

(b) Express - Interior

(c) Express - Baggage compartment

Fig. 2 Interior

of stainless steel. It has been confirmed by a static load analysis/test and crash-worthiness analysis that the carbody satisfies the strength and crash-worthiness performance required by the client.

The front section of the DM and DMB cars consist of an FRP bonnet with an emergency detrainment door.

A floating floor structure, in which the floor panels are supported with rubber, has been adopted to reduce interior noise. A fire resistant structure, in which a thermal insulation is installed between the floor panel and the stainless-steel subfloor, has been adopted to satisfy the standards defined by the National Fire Protection Association (NFPA).

(3) Facilities

Three-pairs of sliding plug passenger doors, which reduce noise, are equipped on each side of passenger cars. DMB cars are baggage cars, and have no windows, and are equipped with five pairs of sliding plug doors on each side of the car.

Figure 2 shows the interior of cars. The seats on Commuter trains are longitudinal seats made of FRP, while those on Express trains are transverse seats with cushions. Commuter trains have two luggage racks for carry-on luggage in each car. Express trains have three luggage racks in each car. Express DMB cars are cars dedicated for baggage and have baggage handling equipment.

The interior of Commuter trains is equipped with two liquid crystal displays for displaying advertisement, news, flight information, etc. (flight information panel: FIP). The interior of Express trains is equipped with four FIPs.

(4) Bogie

Bogie is radius arm type for primary suspension, and bolstered type with air springs for secondary suspension. The bogies are all driving motor bogies to cope with traveling aforementioned long steep gradients along the route.

Conclusion

TTYMRT is currently undergoing a trial run before going into service. When in service, it will directly connect Taoyuan International Airport, Taipei City and Taiwan High Speed Rail, and will contribute to improving airport access, as well as to the development of cities and towns along the route.

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Battery Power System (BPS) for Tokyo Monorail Co., Ltd.

We have delivered above-ground battery power systems (BPSs) to the Shinagawa and Tamagawa substations of Tokyo Monorail Co., Ltd. The purpose of BPSs is to allow monorail trains to run in case of emergency, and is the first of its kind in the world. Even if trains stop between stations due to power failures during the morning rush hour during which trains consisting of the most vehicles run, these systems allow all the vehicles to go to the closest stations trouble-free and passengers to be rescued safely.

Introduction

After the Great East Japan Earthquake hit, there has been a demand to further conserve energy and use power more efficiently. Meanwhile, more and more backup mechanisms that can supply necessary power even after earthquakes and other natural disasters have been introduced.

1 Outline of the system

BPSs have the effect of conserving energy by making effective use of regenerative energy. However, we have an increasing number of projects in which BPSs are used to supply electricity to trains for travel when the power supply from power companies cuts off.

We have delivered BPSs that can follow instantaneous large current of electric railways to many railway companies. In BPSs, our high-capacity nickel-metal hydride batteries GIGACELL, which we developed on our own and can be charged and discharged rapidly, are used.

The total line distance of monorails operated by Tokyo Monorail Co., Ltd. is 17.8 km. Approximately 70% of it is elevated railways and some are over a canal. For this reason, Tokyo Monorail Co., Ltd. was considering introducing means to rescue passengers safely and quickly when trains stopped between stations due to power outages. Therefore, high-capacity BPSs that can be charged and discharged rapidly were installed in the Shinagawa substation in FY2012 and in the Tamagawa substation in FY2013 as shown in Fig. 1 to allow trains with passengers

Fig. 1 Tokyo Monorail route map and BPS installation sites

† Effective use of regenerated energy saves energy, which in turn reduces CO_2 emissions.
High frequency waves that adversely affect surrounding systems are not emitted.

to run to the closest stations. The single BPS in each of the substations consists of two GIGACELL units. A single unit consists of 20 modules. The systems require no power conditioners, so they are directly connected to the feeders. The Shinagawa substation is located underground, so BPS and all other units related to it have been installed indoors. For the Tamagawa substation, only the storage battery board has been installed outdoors due to limited space in the substation.

Table 1 shows the specifications of the BPS installed in each substation. The BPSs delivered to Tokyo Monorail Co., Ltd. this time store regenerative energy from electric trains into high-capacity batteries to stabilize the voltage of the feeders. They use such stored electricity to operate other trains at the time of powering, which allows electricity to be used effectively and in turn possibly allows energy to be saved.

These systems are always monitored by the BPS monitoring and controlling function. If an error occurs, it is displayed on the master unit (monitor) of the BPS monitoring and control panel and alarm signals are sent to the electric power dispatch office in Showajima. In addition, the remote monitoring system displays the error on the remote monitoring device in our company. Figure 2 shows a BPS monitoring screen.

Table 1 BPS specifications

Battery type	Nickel metal–hydride battery
Rated voltage [V]	720
Rated capacity [kWh]	203
Battery module configuration	20 in series and 2 in parallel

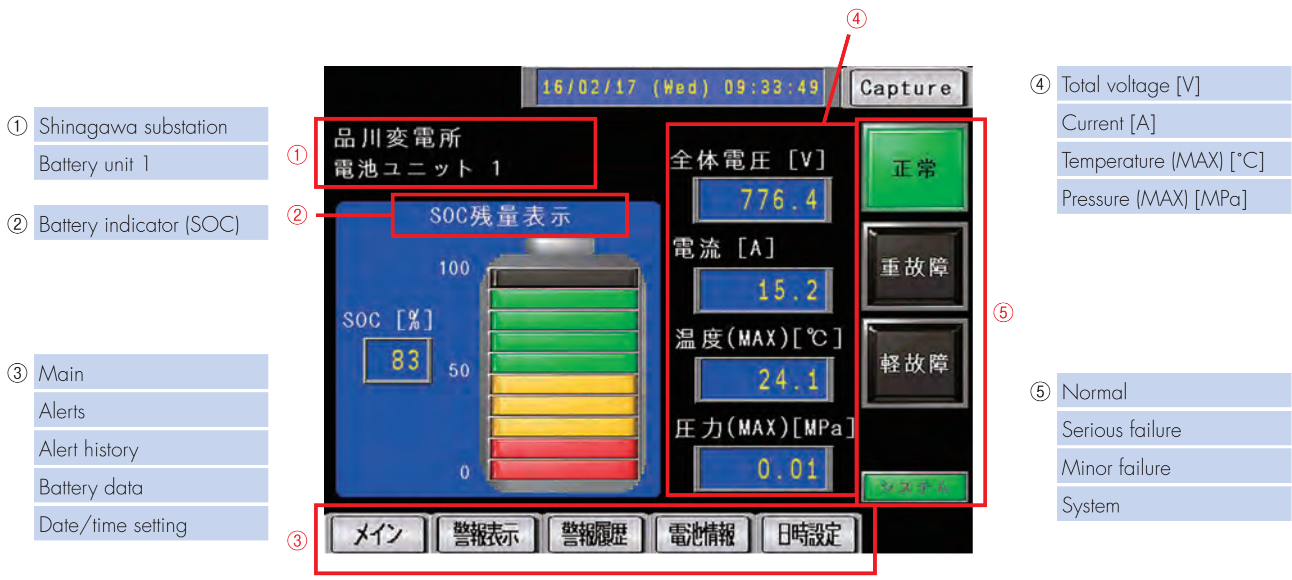


Fig. 2 BPS monitoring screen

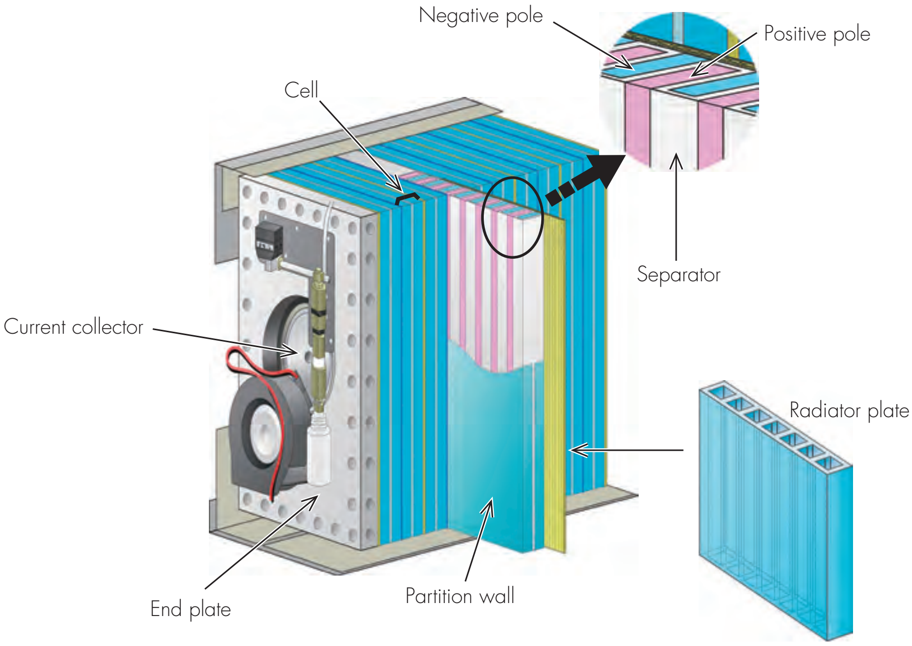
2 Features

Figure 3 (a) is a photograph showing the appearance of the GIGACELL. Figure 3 (b) illustrates the structure (in an actual module, 30 cells are stacked). The GIGACELL has a forced air-cooling and heat release mechanism with a fan and that can reduce the temperature from rising even during charging and discharging at high power.

As characteristics of the GIGACELL, internal resistance is large and its voltage remains almost constant throughout the wide-ranging state of charge (SOC), so the GIGACELL can be directly connected to feeders. The features of the GIGACELL are shown below.

- Does not require choppers that artificially create a certain level of voltage and current from supplied power

(a) Appearance



(b) Structure of module

Fig. 3 GIGACELL, high-capacity nickel metal-hydride battery and other control devices, which can reduce costs for introducing them and footprint.

- Its charging and discharging is highly efficient because it has no control devices that cause efficiency loss.
- Capable of reducing power loss because there is no delays in recovering regenerative energy.
- Does not adversely affect signaling systems (e.g. does not cause electromagnetic interference) because it does not generate noise.
- Allows electricity used to be reduced throughout all time frames, including rush hour, thanks to discharging from the BPS.

3 Effects

(1) Simultaneous operation

The operation of trains can be gradually started in front of ascending slopes where the loads are highest and thereby passengers can be rescued as soon as possible.

(2) Compensating feeding (total travel distance)

If all trains are to run to the closest stations during the morning rush hour for which the schedule is tightest, the estimated total distance is approximately 17 km. On the other hand, the total travel distance for which trains can run only by the BPSs is 25 km and that greatly exceeds the estimated distance of 17 km.

After the BPSs were delivered, Tokyo Monorail Co., Ltd. checked the effects of simultaneous operation and compensating feeding (total travel distance) above.

Conclusion

We will propose and deliver BPSs that can contribute to safety and energy conservation to railway companies in Japan and overseas.

We express our gratitude to Tokyo Monorail Co., Ltd. for adopting the BPSs and providing operation data.

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Kawasaki Heavy Industries Group

Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
Ship & Offshore structure	• LNG carriers, LPG carriers, crude oil carriers, bulk carriers, container ships, car carriers, high-speed vessels, submarines, ships for government and municipal offices, offshore structures	Kobe Works (Kobe, Hyogo Prefecture) Sakaide Works (Sakaide, Kagawa Prefecture) Enseada Industria Naval S.A. (Brazil)* Nantong COSCO KHI Ship Engineering Co., Ltd. (China)* Dalian COSCO KHI Ship Engineering Co., Ltd. (China)*
Rolling Stock	• Train cars, integrated transit systems • Gigacell™ (nickel metal-hydride battery)	Hyogo Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Rail Car, Inc. (U.S.A.)
	• Rotary snowplows, de-icing vehicles • Rail cars, heavy lift cars	Nichijo Manufacturing Co., Ltd. Head Office (Main Plant) (Sapporo, Hokkaido) Nichijo Manufacturing Co., Ltd. Akebono Plant (Sapporo, Hokkaido)
Aerospace	• Aircraft (fixed-wing aircraft and helicopters), missiles, electronic equipment, space systems and peripheral equipment, simulators	Gifu Works (Kakamigahara, Gifu Prefecture) Nagoya Works 1 (Yatomi, Aichi Prefecture) Nagoya Works 2 (Tobishima-mura, Aichi Prefecture)
	• Aircraft components, rocket components, space equipment, target systems • Aircraft servicing, remodeling	NIPPI Corporation Aerospace Division (Yokohama, Kanagawa Prefecture) and Aircraft Maintenance Division (Yamato, Kanagawa Prefecture)
Gas Turbines & Machinery	• Gas turbine engines for aircraft and ships, peripheral equipment • Gas turbine generators, gas turbine cogeneration systems	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
	• Steam turbines, diesel engines, gas engines, large decelerators • Marine propulsion systems (side thrusters, steerable thrusters) • Natural gas compression modules, air blowers and other aerodynamic machinery	Kobe Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Wuhan Kawasaki Marine Machinery Co., Ltd. (China)
	• Air conditioning equipment, general-purpose boilers	Kawasaki Thermal Engineering Co., Ltd. Shiga Works (Kusatsu, Shiga Prefecture) Tongfang Kawasaki Advanced Energy-saving Machine Co., Ltd. (China)*
Plant & Infrastructure Engineering	• Cement, chemical, conveyers, and other industrial plant systems • Industrial boilers for land and marine use • Waste treatment facility • LNG tank and other storage facilities • Shield machines, tunnel boring machines	Harima Works (Harima-cho, Hyogo Prefecture) Shanghai COSCO Kawasaki Heavy Industries Steel Structure Co., Ltd. (China)* Anhui Conch Kawasaki Equipment Manufacturing Co., Ltd. (China)* Anhui Conch Kawasaki Energy Conservation Equipment Manufacturing Co., Ltd. (China)*
	• Crushers, processing equipment for recycling	EarthTechnica Co., Ltd. Yachiyo Works (Yachiyo, Chiba Prefecture)
Motorcycle & Engine	• Motorcycles, ATVs (all-terrain vehicles), recreation ulitity vehicles, utility vehicles, Jet Ski® watercraft • General-purpose gasoline engines	Akashi Works (Akashi, Hyogo Prefecture) Kakogawa Works (Kakogawa, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Motores do Brasil Ltda. (Brazil) India Kawasaki Motors Put. Ltd. (India) Kawasaki Motors Enterprise (Thailand) Co., Ltd. (Thailand) PT. Kawasaki Motor Indonesia (Indonesia) Kawasaki Motors (Phils.) Corporation (Philippines) Changzhou Kawasaki and Kwang Yang Engine Co., Ltd. (China)*
Precision Machinery	• Hydraulic equipment for construction machines, hydraulic equipment and systems for industrial machines • Marine application machines, deck cranes and other marine deck equipment • Industrial robots • Medical and pharmaceutical robot	Akashi Works (Akashi, Hyogo Prefecture) Nishi-Kobe Works (Kobe, Hyogo Prefecture) Kawasaki Precision Machinery (U.K.) Ltd. (U.K.) Wipro Kawasaki Precision Machinery Private Limited (India) Kawasaki Precision Machinery (Suzhou) Ltd. (China) Kawasaki Chunhui Precision Machinery (Zhejiang) Ltd. (China) Flutek, Ltd. (Korea)

*Affiliated company-equity method

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