History of Air Spring Development for Shinkansen Trains

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Air springs are part of a soft damping suspension system that provides both softness and damping characteristics by utilizing the compressibility and flow resistance of air. They were first used on railways about 60 years ago. The subsequent and continuous advancement of air spring technology is a result of the incorporation of air springs into Shinkansen trains and the acceleration of R&D activities in overcoming various challenges associated with increasing train speeds. To reduce the environmental impact of high-speed trains, the weight of each car was reduced dramatically. In particular, adoption of bolster-less bogies reduced car weight. Together with such technological innovations, the functions of air springs also changed remarkably. To make the Shinkansen competitive with aircraft by increasing both speed and ride quality, various new functional units were developed. Such units include the horizontally nonlinear air suspension system and the car-body tilting system with built-in air springs that enables trains to travel at higher speeds on curved tracks. A project aimed at further increasing train speed has been launched for several train lines. We will continue our R&D efforts to develop air springs that will enable trains to run safely at speeds exceeding 320 km/h while providing a truly comfortable ride.

Keywords: air spring, Shinkansen (bullet train), railway vehicle, bogie, secondary suspension

1. Introduction

Air springs are soft suspension parts that offer damping characteristics by utilizing the compressibility and flow resistance of a gas (air).

In the U.S., air springs came into general use in the 1940s, mainly for long-distance buses, and spread to railway vehicles in the 1950s. In Japan, a triple convolution air spring (hereafter, bellow spring) was adopted in the DT23 bogie[1] (electric multiple unit 151 series), which was the culmination of product development from a variety of research that had been started by the High-Speed Bogie Vibration Research Group, established after World War II. The softness of the bellow spring improved ride quality, while its leveling valve allowed for carriage height control. Since its adoption, air springs came to be regarded as a highly important component of bogies.

In general, a bogie has primary and secondary suspension systems, of which the former is installed between the wheel axle and the bogie frame, while the latter is installed between the bogie and the vehicle body to support the vehicle body. An air spring is used in the secondary suspension system, and the purpose of this spring in swing hanger bolster device (as in the DT23 bogie) was to alleviate vertical motion.

Since the adoption of air springs in the first generation—0 (zero) series- Shinkansen (bullet train), air spring functions diversified as Shinkansen bogies changed their structures, thereby requiring new bogie design technology. This resulted in demands for additional functionality in air springs, as well as motion damping capabilities in different directions. Throughout the 50 years or so since the inauguration of Shinkansen services, top speeds have increased from 210 km/h to 320 km/h through vehicle weight reduction and performance improvements. Ride quality has also been ensured through the development of a variety of vehicle motion control technologies.

This paper discusses the technological advancement of air springs, which are one of the most important safety components in a bogie, in order to adapt to the new technological developments in Shinkansen trains.

2. Air Springs

Air springs are a suspension system that offers softness and high damping characteristics by utilizing air compressibility and flow resistance within a pipeline. Figure 1 shows a conceptual diagram and a vibration model of an air spring. The following is an explanation of an air spring mechanism using a conceptual diagram. Air is enclosed within the components shown in the diagram. The vertical movement of the main chamber, which is surrounded by an outer cylinder, inner cylinder, and diaphragm, changes the air volume within the chamber to create pressure fluctuation. Due to this pressure fluctuation, compressed air flows through the orifice, and then spring and damping effects are created. In the air spring vibration model, k_1 refers to the stiffness of the main air spring

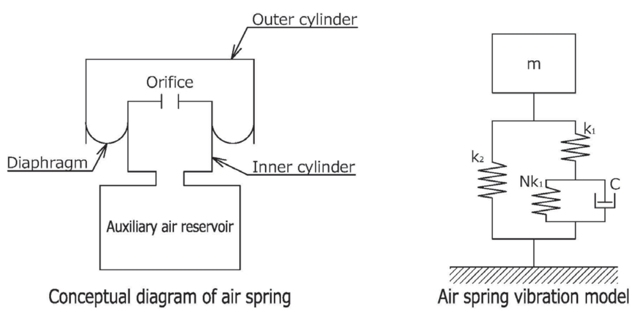

Fig. 1. Conceptual diagram and vibration model of air spring

chamber (internal volume part), k_2 refers to the stiffness of the changes in the effective surface area, N refers to the volume ratio between the internal volume and auxiliary air reservoir volume, and Nk_1 refers to the stiffness of the auxiliary air reservoir. C represents the damping coefficient of the orifice aperture.[2] The damping performance and stiffness reduction in the vertical spring constant can be controlled by changing the volume of the auxiliary air reservoir and orifice diameter in order to design air springs with varying characteristics to suit different purposes, as well as delivering the required functionality and performance. The air spring is also featured by its capability to maintain a constant height, regardless of the weight loaded on it by supplying and releasing the internal air using a leveling valve.

3. Challenges Faced in the "0 Series" Shinkansen

For the bogie (Fig. 2) in the first generation of Shinkansen that aimed at high-speed velocity with a maximum of more than 200 km/h, it was decided not to employ the swing hanger bolster device to buffer the lateral motion. Instead, a simple and lightweight vehicle support device was adopted, in which an air spring was directly mounted on a bolster.[3]

In this device, the air spring was required to have both vertical and lateral characteristics. Regarding the lateral direction, the air spring was also needed to recover the relative displacement between the bogie and the vehicle body (i.e. re-centering bogie and vehicle body) by its lateral reaction force. The challenge here was to develop an air spring that delivered excellent spring characteristics not only in the vertical direction, but also in the lateral direction.

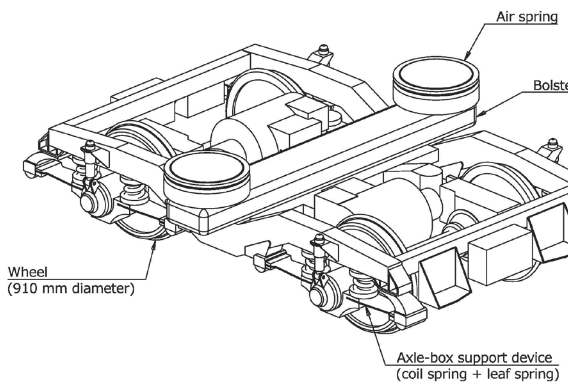

Fig. 2. Direct mount bogie

3-1 Development of a guided rolling diaphragm air spring

The prototype created in the early development stage was based on the standard bellow air spring with improved resilience. As shown in Fig. 3, it comprised bellows with three convolutions sandwiched by the top and bottom plates, in which the lateral stiffness depended on the stiffness of the bellow skin. The test results showed high hysteresis in lateral force-displacement because the spring constant largely depended on the input lateral amplitude. Thus, the resilience performance was not good. Also, there were some instability factors, such as significant variations in the lateral spring constant depending on the height settings of the device installation.

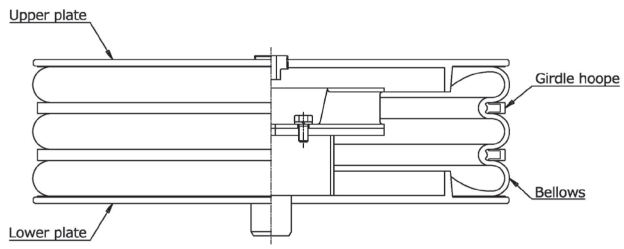

Fig. 3. Triple-convolution bellows type air spring

An air spring with a guided rolling diaphragm (hereafter, diaphragm spring), which was eventually developed by Sumitomo Electric Industries, Ltd. (Sumitomo Electric) and Sumitomo Metal Industries, Ltd. (current Nippon Steel & Sumitomo Metal Corporation) had a structure in which a diaphragm was sandwiched between the walls of the outer and inner cylinders, as shown in Fig. 4. The lateral reaction force of the air created by these walls is the main component of lateral stiffness. This structure also enabled the vertical and lateral spring constants to be controlled by the angle of these walls.

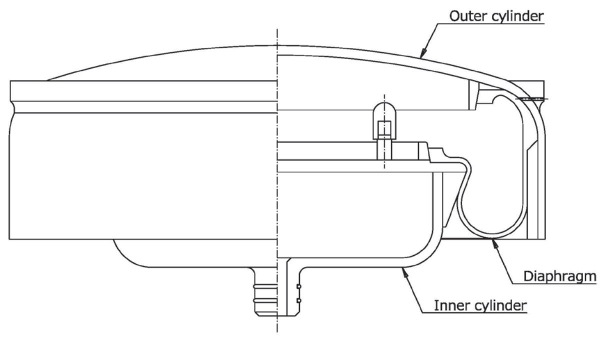

Fig. 4. Guided rolling diaphragm air spring

The basic characteristics of the diaphragm spring compared to the bellow spring are as follows:

(1) The vertical spring constant becomes softer when the internal volume and the volume of the auxiliary air reservoir are the same.

(2) The main component of the lateral stiffness is the reaction force of the air, which provides stable displacement recovery. Figure 5 represents the measurement results

of the correlation between the lateral reaction force and displacement. It is clear that the diaphragm spring has small hysteresis and large reaction force.

According to the results of a running test conducted by Japanese National Railways (current Japan Railway Company: JR), the bellow type spring was rejected due to unresolved fatal deficiencies related to its vibration characteristics and the recentering of the bogie and vehicle body. Instead, the diaphragm type spring was adopted in Shinkansen trains.(4)

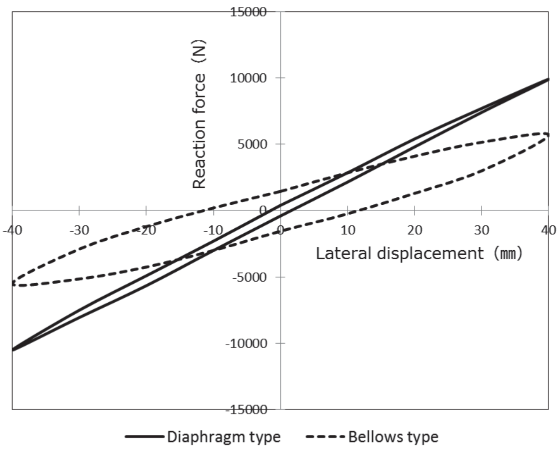

Fig. 5. Reaction force vs Lateral displacement

In the more detailed design of the diaphragm spring, we decided to use a self-sealing diaphragm for its ease of assembly, disassembly, and maintenance. Although this spring has a disadvantage in terms of weight as it uses many metal components, weight reduction was addressed by using an aluminum alloy for all the metal components.

The basic design of the 0 series Shinkansen bogie (DT200) was inherited by the 200 series Shinkansen bogie (DT201 for the Tohoku and Joetsu Shinkansen) and the 100 series Shinkansen bogie (DT202 for the Tokaido and Sanyo Shinkansen). This basic design of the diaphragm spring was used until the bolsterless bogie was adopted in later Shinkansen.

4 Speed Increase and Weight Reduction for Shinkansen Trains

In the 1980s, research and development on further increases in speed were made. Along with this research, research continued on air springs in order to improve ride quality at higher speeds and reduce vehicle weight for environmental protection. This research included (1) improvement of the spring constant flexibility for better ride quality, and (2) development of an air spring for the lightweight bolsterless bogie.

4-1 Increase in spring constant flexibility

To improve ride quality in the 0 series Shinkansen,(5) researches on the effects of reducing the lateral spring constant on ride quality began. Based on the original 0 series air spring structure, we created a test spring with 3/4 stiffness (compared to the DT201 bogie) by reducing the lateral air reaction force through altering the angles of the diaphragm walls. We also created another test spring with 1/2 lateral stiffness by laying laminated rubber in an array to maximize flexibility. When these were used in actual running tests, it was found out that the lateral stiffness reduction was effective in improving ride quality. The maximum speed of the 100 series Shinkansen, the fully remodeled version of the 0 series, was planned to be 230 km/h. To improve ride quality at this speed, the spring with 3/4 stiffness with angled outer and inner cylinder walls was adopted and mass-produced.

4-2 The Lightweight Bolsterless Bogie

In order for the Shinkansen to compete with air travel, it was said that the train had be able to travel between Tokyo and Shin-Osaka in 2 hours 30 minutes. To achieve this, it was necessary to increase the maximum speed of the Shinkansen to a range between 270 and 300 km/h. The challenges associated with this speed increase were conformity to environmental specifications in terms of noise and vibration for areas along the railway, and ensuring ride quality. The axle load of the 0 series bogie at the maximum speed of 220 km/h was 16 tons (the vehicle weight was 64 tons). While traveling at the maximum speed of 270 km/h, to keep the noise and vibration levels in the bolsterless bogie at the same or less level than those of the 0 series, the axle load had to be held to 11.3 tons at most.(6) To attain this requirement, the scope of research covered even the structural design of the body and bogie and this eventually led to the decision to employ a lightweight structure design of bogie and aluminum alloy for the body. The design plan adopted to reduce the bogie weight included elimination of a bolster, and usage of a hollow axle and small-diameter wheels. This was the first utilization of a bolsterless bogie (Fig. 6) in Shinkansen trains, achieving a 30% weight reduction in the bogie.(7)

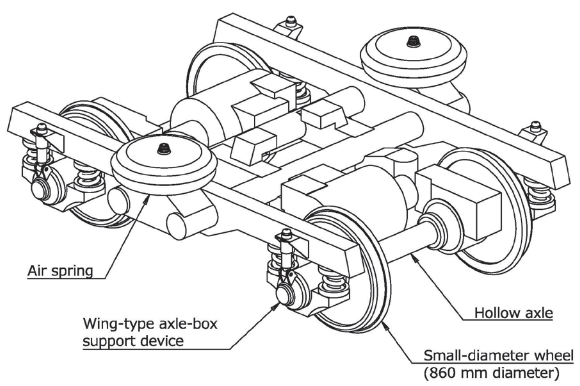

Fig. 6. Bolsterless bogie

4-3 Development of an air spring for the bolsterless bogie

In a conventional bolster bogie, rotation occurs between the bogie frame and the bolster following the curve of the rail as it moves.

In a bolsterless bogie, a vehicle body is directly supported by an air spring that allows longitudinal displacement of ±100 mm or greater. When a train travels on a curved railway, the bogie stably rotates against the body movement through a large longitudinal displacement provided by the air spring.

Thus, another requirement of having permitted longitudinal displacement of ±100 mm or greater was added to the specification of Shinkansen air spring, and tests on functions, performance, and durability were conducted. Further, the air spring with large longitudinal displacement usually used a fastened diaphragm, however, the air spring to be used for the bolsterless bogie for Shinkansen was required to be the self-sealing type. This was in order to keep maintenance procedures for the air spring in the bolsterless bogie the same as the previously used self-sealing diaphragm spring in the conventional Shinkansen.

The large longitudinal displacement in the air spring was realized by combining the diaphragm and laminated rubber so that the rubber stopper also delivered some of the displacement. With this mechanism, more flexibility was added in the lateral spring constant making the resulting air spring's stiffness about 60% of that in the 100 series Shinkansen (Fig. 7). Also, the variable orifice diameter equipment,[2] which was studied in the Railway Technical Research Institute in 1981, was adopted as the function to deliver stable damping of the vertical movement regardless of the amplitude of vibrations.

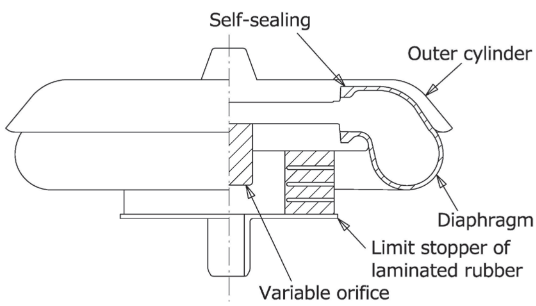

Fig. 7. Air spring for bolsterless bogie

The new Shinkansen featuring these new technologies appeared as the 300 series Shinkansen (Nozomi), that was operated between Tokyo and Osaka by Central Japan Railway Company (JR Central) at a maximum speed of 270 km/h with a minimum duration of 2 hours and 30 minutes. This train was also adopted by West Japan Railway Company (JR West) and all Shinkansen trains introduced after this time use the bolsterless bogie.

5. Adapting to Faster Speeds

In the 1990s, railway and flight services started seriously competing to secure customers traveling between Tokyo and Hakata, Kyushu. JR Central and JR West commenced the development of the post-300 series Shinkansen for even faster traveling velocities to directly take on the airlines. To verify the next-generation Shinkansen technology, JR Central produced the 300X and JR West produced the WIN350 and put these models through high-speed running tests.

Based on the test results, JR West started development of the 500 series Shinkansen that aimed to run at a maximum speed of 320 km/h. The test results also encouraged JR Central to commence development of the 700 series Shinkansen, with the aim of offering a better passenger environment and comfort, and an increase in the maximum speed within the Sanyo Shinkansen region from 270 km/h to 285 km/h.

In terms of air spring development, there was an issue to address concerning ride quality improvements when traveling on curved railways at increased speeds. Possible solutions included elimination of collisions of the lateral bumpers, and applying an air spring to the body tilting device. The conventional Shinkansen faced an issue whereby the lateral bumper of the bogie would strike the lateral stopper of the body at increased speeds on curved railway due to the excess centrifugal force created by the high speed pushing the body outwards to its maximum possible position. With this collision, the rate of acceleration increased causing the passengers some discomfort.

5-1 Development of the nonlinear air spring

The body and bogie are both designed to offset the force whereby the body tilts outwards on a curved railway due to centrifugal force, and the force whereby the body falls inwards due to its weight and the tilting. This offset value is set by the curve radius and driving speed in combination with "super-elevation" (the difference in height of the inner and outer rails) (Fig. 8).

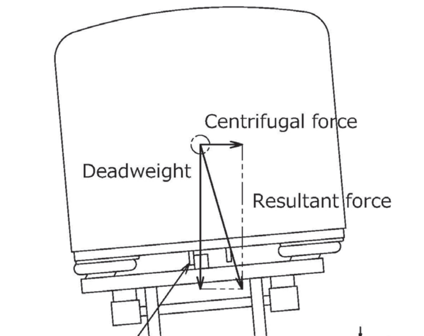

Fig. 8. Cant and centrifugal force applied to vehicle

If a train passes through a curved railway at more than the specified speed, excess centrifugal force is generated and this pushes the carriage outside of the curve. To limit this amount of displacement within the architectural limits, lateral bumpers are installed between the body and bogie. If the air spring's reaction force is greater than the centrifugal force, this contact can be avoided. The air spring's reaction force is small because its lateral spring constant is designed to be soft to provide passenger comfort. However, adding nonlinear characteristics as shown in Fig. 9 can ensure a reaction force from the air spring equivalent to the centrifugal force.

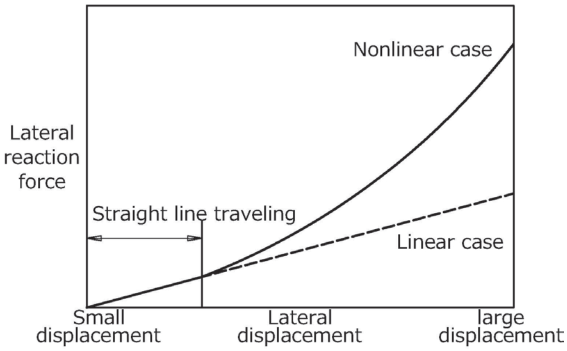

Fig. 9. Nonlinear characteristics of lateral direction

The requirements for an air spring are having low stiffness and linear characteristics in the lateral displacement area when running in a straight railway; showing increased lateral stiffness during the increased degree of lateral displacement; and maintaining the displacement level within a range that does not cause bumper collisions. This is achieved by the air spring's reaction force.

To tackle this challenge, a stopper of laminated rubber and an outer cylinder skirt were installed in the lateral direction as a part of the air spring (Fig. 10). When the displacement is small, the spring constant remains soft. When the lateral displacement grows larger, the lateral stopper of provides rigidity and the diaphragm touches the outer cylinder skirt increasing the air reaction force (Fig. 11). This mechanism is installed for lateral motion only. For the longitudinal direction, the gap between the stoppers is wider and no skirt is installed. This ensures the softness while the bogie is rotating.

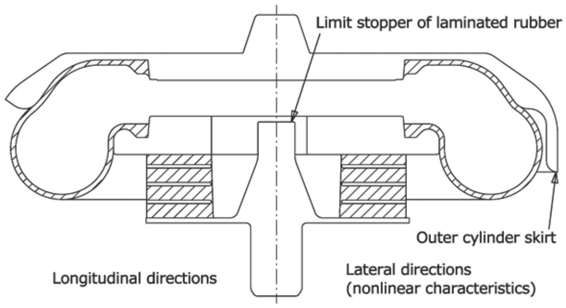

Fig. 10. Structure of nonlinear characteristics air spring

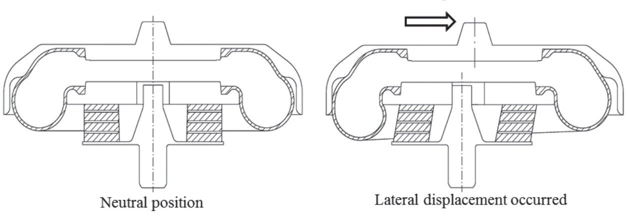

Fig. 11. Motion diagram of nonlinear characteristics air spring

Since 1993, Sumitomo Electric Industries, Ltd. has worked together with JR Central to find the means to resolve issues such as these. The intellectual property rights concerning this technology are jointly owned by the two companies.[8] After confirming the efficacy of this technology by running tests using actual trains, this spring was adopted in mass-production for the 700 series.

This nonlinear technology improves ride quality without stopper collisions even when passing through curved railways with an insufficient level of cant at higher speeds. In the production model, this stopper gap was increased within the permissible architectural limits, and a high reaction force is secured by increasing the amount of lateral displacement of the air spring.

This technology was later employed by many Shinkansen trains and became the standard structural technology for Shinkansen air springs.

5-2 Speed increase through vehicle tilting

To shorten the transportation time of Shinkansen travel in Japan, speed increase at curved railways was essential. To increase the traveling speed on curved railways while ensuring the safety and comfort of passengers, it was necessary to reduce the loading from excess centrifugal forces on passengers, and implement countermeasures for lateral bumper collisions at the same time.

In 2005, development began for a new car that could travel on the curved railways of the Tokaido line at 270 km/h. To increase the curve travelling speed without changing the cant level, it was necessary to install a body tilting device on the bogie to compensate for the insufficient level of cant as shown in Fig. 12. However, a pendulum bogie design was not chosen due to increased complications in the mechanism and gains in bogie weight. Instead, a side-lifting mechanism using an air spring with asymmetrical strokes was employed. A train using this mechanism started service as the N700 series from July 1, 2007 to promote higher speed traveling. The maximum tilt angle was set to 1 degree.[9]

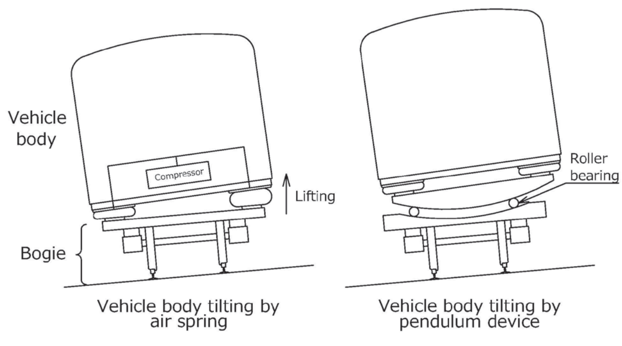

Fig. 12. Vehicle body tilting when traveling curved railway

As the second phase of increasing speed, the N700A series, an enhanced model of the N700 series, was introduced to achieve 285 km/h over curves. In this model, an air spring with better reaction force value deriving from its nonlinear characteristics was employed.

East Japan Railway Company (JR East) also conducted a variety of assessments on increasing speed and reliability, environmental protection conformity, and passenger comfort using the Shinkansen high-speed test train called FASTEC360[10] from about 2006. This resulted in the mass-production of the E5 and E6 series, and our nonlinear air spring was also customized and used in these trains. These air springs were also equipped with asymmetrical strokes to deliver the side-lifting mechanism for carriage tilting, in the same manner as in the N700 series.

6. Conclusion

This paper discussed the advancement of air spring technologies developed alongside the further innovations made in Shinkansen trains technology since the beginning of its operations. Air spring enhancements have so far been made mainly in the mechanical and structural areas; however, future requirements will also include control technologies to enable functioning as a part of a larger system. We are sure that we will meet even higher standards of requirements for even faster traveling speeds, ensuring reliability, conforming to environmental restrictions, and providing an even better passenger experience.

The history of air spring technology development for Shinkansen trains is the history of conquering the challenges presented by attempting to realize a high-speed train service within the small and complicated landscape of Japan. The Shinkansen technologies are sure to continue to propagate throughout the world in the future, and we will face new challenges there. However, we hope that we can find some clues for effective solutions from the expertise that we have developed throughout this history.

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