Simulation Technology for Air Springs of Railway Systems

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The air spring is an essential component for improving the comfort of railway vehicles and realizing safe high-speed driving. Due to the growing urban population and increased concern about environmental issues, railways are attracting attention because they have higher transportation efficiency than automobiles and aircraft and contribute to the reduction of CO_2 emissions and energy consumption. As the railway network spreads all over the world, air springs with various characteristics are required depending on the route and environment. To respond to such market needs and make proposals in a speedy manner, we are developing innovative design methods based on computer simulation. This time, we have developed a simulation technology that accurately predicts the static and dynamic characteristics of air springs.

Keywords: air spring, composite material, simulation, prediction technology, vibration characteristics

1. Introduction

With an increase in urban population and growing concern about environmental issues, railways are drawing attention because their transportation efficiency is higher than that of automobiles and aircraft. Countries around the world are promoting the development of railway networks. In the railway networks now spreading world-wide, air springs are essential components for improving the ride comfort of vehicles and guaranteeing safe high-speed running.

Demand for air springs with a wide variety of spring characteristics is growing to ensure the safe, comfortable, and high-speed running of vehicles on train lines and in the environments where railways are constructed.[1],[2] In response to the above situation, Sumitomo Electric Industries, Ltd. has been developing a new quick design technology of air springs by employing a spring characteristics simulation technique and thus enable supply of air springs meeting a variety of needs. In line with the above development objective, we have developed a computer simulation technology to accurately predict two particularly important air spring characteristics that affect the ride comfort of railway vehicles. One of these characteristics is the spring constant that represents the reaction force characteristics of an air spring when it supports a vehicle body in a static state, while the other is vibration transmissibility that represents the ease of vibration transmission from the bogie to the body of the vehicle in a dynamic state. This paper describes the details of the new air spring design technology.

2. Structure and Function of Air Spring

An air spring for a railway vehicle is schematically illustrated in Fig. 1. An air spring is composed of two key components: a diaphragm and laminated rubber, and is installed between the bogie and body of the railway vehicle.[3]

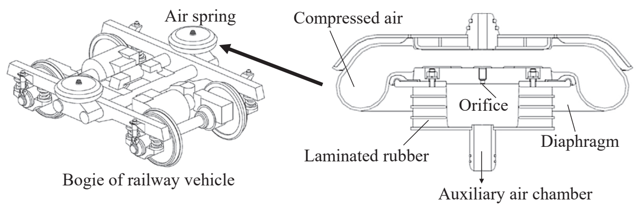

Fig. 1. Bogie of railway vehicle and air spring for railway vehicle

The diaphragm is made of rubber having excellent flexibility and airtightness, and is strengthened by embedded reinforcing fibers. Compressed air contained in the diaphragm supports the vehicle body. The diaphragm is connected to an auxiliary air chamber via a pipe fitted with an orifice. Compressed air moves back and forth between the diaphragm and auxiliary air chamber as the vehicle body vibrates. The fluid resistance generated in the pipe absorbs the vibration and improves the ride comfort of the vehicle.

The laminated rubber is connected to the bottom of the diaphragm and assures the minimum necessary ride comfort and safety in the case that the diaphragm leaks air (blows out) while the vehicle is running.

The simulation technology for the diaphragm, which is the most important functional component of an air spring, is described below.

3. Development of Air Spring Characteristics Prediction Technology

3-1 Development goal

The following two characteristics of air springs for railway vehicles strongly affect the ride comfort of vehicles. One is a spring constant that represents the load required to displace the air spring in the compression (vertical) or shear (lateral) direction, while the other is vibration transmissibility that represents the ratio of vehicle body vibration amplitude to bogie vibration amplitude. In the development of the new simulation technology, we aimed to accurately predict the above two characteristics.

Among air spring components, the diaphragm is mainly responsible for the spring constant, and the system comprising the diaphragm with pipe and the auxiliary air chamber is responsible for vibration transmissibility.[4]

In the development of the new simulation technology, we started with accurate modeling of a diaphragm that affects both spring constant and vibration transmissibility. Using this model, we built a technology for predicting the spring constant and vibration transmissibility, the main characteristics of an air spring.

3-2 Modeling of diaphragm

A diaphragm is made of a composite material with angularly distributed reinforcing fibers embedded in its curved rubber. The rigidity of the reinforcing fibers is 100 times or more that of the base rubber and significantly affects the spring constant of the air spring. This means that accurately modeling the angular distribution of the reinforcing fibers is indispensable for accurately predicting the characteristics of the air spring.

To accurately model the angular distribution of the reinforcing fibers, we focused on the diaphragm production process. In the diaphragm production process, a cylindrically formed fiber-reinforced rubber piece is fitted into a mold and compressed under high-temperature, high-pressure gas ambience to mold the rubber piece into a predetermined diaphragm shape. The cylindrically formed fiber-reinforced rubber piece, if it is not yet molded, can be accurately modeled based on the relevant design drawing in which the reinforcing fiber embedding angle is indicated. In the development of a simulation technology for predicting the angular distribution of the reinforcing fibers in a diaphragm completed by deforming a cylindrically formed fiber-reinforced rubber piece, we introduced a technique that can analyze the non-linear variation of the angle of reinforcing fibers embedded in the rubber (see Fig. 2).

To verify the validity of the angular distribution of reinforcing fibers predicted by simulation, we carried out a nondestructive investigation of the angular distribution using an X-ray CT (computed tomography).

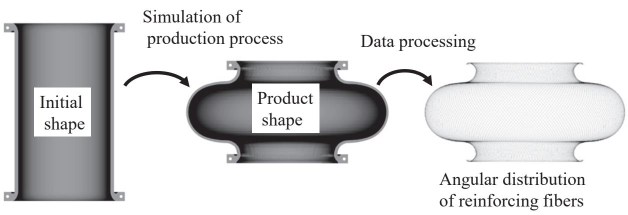

Fig. 2. Simulation of the angular distribution of reinforcing fiber

An industrial air spring, which is smaller than air springs for railway vehicles, was used as a test specimen for the verification. Figure 3 shows the verification results. The angular distribution of the reinforcing fibers in the diaphragm could be accurately predicted by simulating the diaphragm production process.

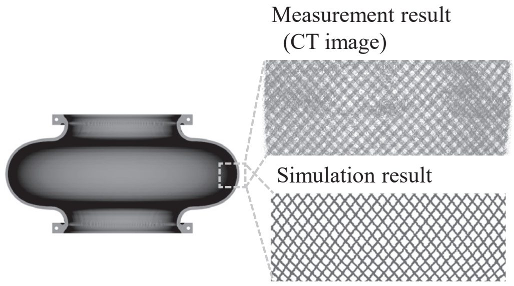

Fig. 3. Simulation result for the angular distribution of reinforcing fibers

3-3 Prediction of spring constant

Using the diaphragm model predicted by simulating the production process of air springs for railway vehicles, we simulated both the vertical and lateral spring constants of the diaphragm. As can be seen from the simulation results shown in Fig. 4, both the predicted vertical and lateral spring constants agreed well with the measured values. In this manner, we have established a technology that can predict spring constants, the principal characteristics of an air spring, with a high degree of accuracy.

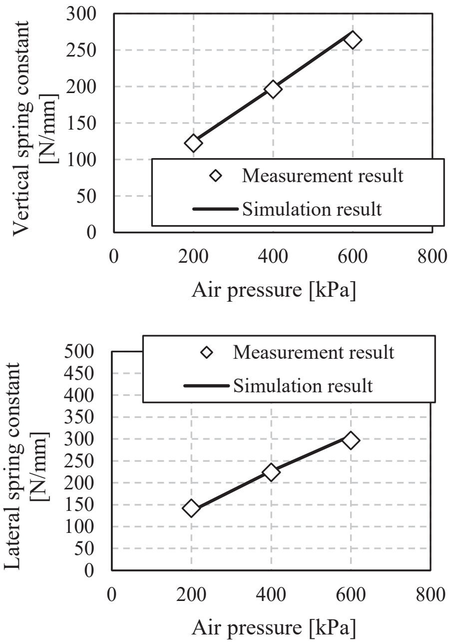

Fig. 4. (Top): vertical spring constant
(Bottom): lateral spring constant

3-4 Prediction of vibration transmissibility

The vibration characteristics of an air spring are schematically illustrated in Fig. 5 (a). When the bogie vibrates, the air spring expands and contracts and compressed air flows back and forth between the spring interior and auxiliary air chamber via the pipe. The fluid resistance produced by the movement of compressed air absorbs the vibration energy and damps vehicle body vibration. Since passengers' discomfort due to vehicle vibration depends on the vibration frequency,[5] air springs should be designed so as to damp vibration in a human-sensitive frequency band. The vibration characteristics required of an air spring are that it resonates at a low frequency that is not sensed by passengers and damps high-frequency vibrations.

As shown in Fig. 5 (b), the vibration of an air spring can be represented by a model that combines the spring and dashpot.[6] In this figure, symbol M represents vehicle body mass, k_1 represents the vertical spring constant of the air spring, k_2 represents a change in diaphragm internal pressure, N represents the volume ratio between the diaphragm and auxiliary air chamber, Nk_2 represents a change in auxiliary air chamber internal pressure, and C represents the fluid resistance produced in the pipe.

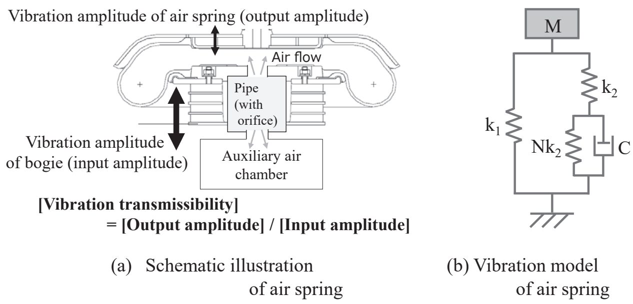

Fig. 5. Schematic illustration of air spring and its vibration model

Here, all parameters other than the fluid resistance C can be obtained by simulating vertical spring constant as described above. To determine the fluid resistance C, we modeled the pipe for the air spring to simulate the behavior of compressed air inside the pipe when the air spring vibrates. Figure 6 shows the vibration transmissibility calculation results. For the calculation, each parameter of the vibration model was determined by simulating the vertical spring constant of the air spring and the flow of compressed air in the air spring pipe. It was confirmed from this figure that the principal characteristics of air springs that greatly affect the ride comfort of the railway vehicle, such as resonance frequency, the peak value of vibration transmissibility, and high-frequency damping characteristics, can be accurately predicted by simulation.

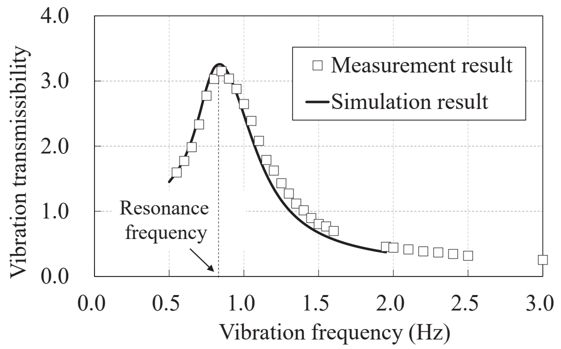

Fig. 6. Vibration transmissibility simulation result

As described above, we have developed a technology that can accurately predict the spring constant and vibration transmissibility of air springs from their design information.

4. Use of New Technology for Air Spring Design

The characteristics required of air springs for railway vehicles are determined to ensure optimal ride comfort after predicting the weight of each vehicle body and the acceleration the body will receive on a railway track. Since the weight and acceleration of the body fluctuate depending on the number of passengers, the fluctuation amounts are compensated for by adjusting the compressed air pressure in the diaphragm. This means that the characteristics required of air springs include vertical and lateral spring constants at various compressed air pressures. In air spring design, it is necessary to devise the structure of an air spring that can exhibit these characteristics at the same time. However, only highly skilled air spring designers can devise air springs meeting the requirements for specific characteristics. The newly developed simulation technology makes it possible for even inexperienced design engineers to efficiently follow the design and verification cycle and thereby save prototyping man-hours necessary for meeting specific requirements.

An example of the application of the new simulation technology to an actual air spring design is described below. On a certain route, railway vehicles were estimated to receive a higher lateral acceleration than on the other routes. If these vehicles were equipped with air springs having a lateral spring constant equal to that of conventional air springs, the vehicles would roll greatly, degrading their ride comfort. To prevent the degradation of ride comfort, we were required to improve only the lateral spring constant of the air springs while keeping their vertical spring constant equivalent to that of conventional air springs. An example of a design change by employing the newly developed air spring simulation technology is shown in Fig. 7. Pre-simulation made it possible to design air springs meeting customer requirements.

As described above, the newly developed simulation technology enables investigation of the effects of design changes in advance, eliminating the need to redesign air

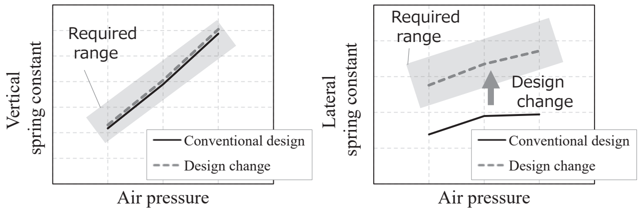

Fig. 7. Prediction result for air spring characteristics after structural change

springs after prototyping, and saving design man-hours.

5. Conclusion

We have developed a new simulation technology that can accurately predict the spring constant and vibration transmissibility of air springs at their design stage in advance of prototyping. The new technology saves air spring prototyping man-hours at the design stage. This technology is expected to meet various needs for air springs in the world and also to contribute to further evolution of vehicle technology.

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