1. Introduction
In recent years, buildings in overseas countries have become very tall, with some exceeding 800 m in height. There are also buildings being planned that will be more than 1 km tall. As buildings become taller, there is growing demand for elevators that travel faster. To meet these demands, Mitsubishi Electric has developed an ultra-high-speed elevator capable of traveling at 1,080 m/min, which is considerably faster than the 750-m/min elevator developed by us in the past. During the development of faster elevators, we faced many issues that did not appear in the conventional speed range, and also issues arising due to the ultra-high lift. This paper focuses on the comfort of ultra-high-speed elevators, and describes measures for suppressing vibration inside the car, measures for reducing noise inside the car, and methods of mitigating the sensation of compression in the ears experienced by persons riding the elevator. It also introduces issues peculiar to an ultra-high-speed elevator related to these technologies, and the development of elemental technologies for overcoming these issues.

2. Technology for Suppressing Vibration Inside the Car

2.1 Technology for damping vibration in a high-speed elevator
When an elevator travels, its guide unit follows a rail installed in the hoistway, so any minute curvature of the rail itself or minute buckling of the rail joints will exert an excitation force on the car. With high-speed elevators in the past, good riding comfort was achieved by improving the machining accuracy of the rail itself, and also by controlling installation accuracy and using passive dampers. With the appearance of the active roller guide in 2003, it became possible to offer greater riding comfort than that of conventional high-speed elevators by using an actuator to cancel out the excitation force on the rail.

Looking at the configuration of an elevator car, the car frame is supported by the rail with vibration-damping material between them, and also the car is supported by the frame via isolating rubber, resulting in a complicated vibration mode. Figure 1 shows an example of the results of analysis. The vibration modes of the car frame and the car are in-phase at low speed, and in opposite phases at ultra-high-speed. Conventional vibration suppression involves suppressing the vibration of the car in which the vibration of the car frame is observed and its vibration is damped, thereby suppressing the vibration of the car, which is generated in the same phase as the car frame. Consequently, in order to effectively suppress vibration, it is necessary to detect the vibration of the car.

2.2 Issues related to ultra-high-speed (1)
The frequency of the excitation received by the elevator from the rail is determined by the correlation between the elevator speed and the length of the rail (V/L), as shown in Table 1. Conventionally, the center of the excitation frequency range is about 2.5 Hz. However, at higher speeds, it will shift to the high-frequency side and become about 3.5 Hz. This value is the excitation frequency corresponding to the case where the rail is warped in the shape of a bow. When the elevator travels along a rail that is warped in a complicated shape such as an “S” or “W” shape, the excitation frequency will shift even further to the high-frequency side.

### Table 1 Frequency of excitation transmitted from the rail

<table>
<thead>
<tr>
<th>Speed V (m/sec)</th>
<th>Rail length L (m)</th>
<th>Excitation frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-high-speed (conventional elevator)</td>
<td>12.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Ultra-high-speed (developed elevator)</td>
<td>18.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

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2.3 Issues related to ultra-high-speed (2)

When an elevator travels at high speed, not only does noise inside the car increase, but also an excitation force due to wind pressure acts on it, as described below. When a single elevator is operating independently of other elevators, it is not greatly affected by these forces, but if it passes an adjacent elevator at high speed, a wind force of several hundred N will act on the sides of the car, so it is necessary to devise measures to minimize isolated horizontal vibration.

2.4 Active roller guide for ultra-high-speed use

An active roller guide for an ultra-high-speed elevator involves the use of acceleration sensors installed on both the car and the car frame (Fig. 2). These enable the vibration of the car to be suppressed in an observable condition. The system can therefore minimize the effects of changes in the vibration mode of the car from low speed to ultra-high-speed, and also the excitation force due to wind which acts directly on the car. In addition, the roller guide proper and the linear motor-type actuator are optimally designed for ultra-high-speed use.

As a result of this system, the riding quality which significantly deteriorated at high speed can be improved to the same level as that using conventional active vibration suppression, when the elevator is accelerating and decelerating and also traveling at the maximum speed of 1,080 m/min.

3. Technology for Reducing Noise in the Car

The noise level in the car in a moving elevator increases in proportion to the speed. Noise inside the car is classified into solid propagation noise due mainly to excitation from the cables and the rail, and air propagation noise in which fluid noise (wind noise) propagates in the air in the vicinity of the car. As the speed of the elevator rises into the ultra-high-speed (exceeding 750 m/min) region, the predominant noise inside the car tends to be fluid noise. This fluid noise is estimated to be proportional to between the 5th and 6th power of the elevator speed. It is estimated that if the car of an existing Mitsubishi elevator designed to run at up to 750 m/min is made to travel at 1,080 m/min, for example, the level of noise inside the car would increase by approximately 10 dB (A). The question of how to reduce this increase of approximately 10 dB (A) was a technical issue related to the current development of an ultra-high-speed elevator.

Technology for reducing the noise generated in the car of an ultra-high-speed elevator involves the following two themes:

1. A method of reducing the noise source in the vicinity of the car
2. Improvement of soundproofing of the car structure

The technical issues related to these themes and also the details of the development process for solving these issues are described below.

3.1 Mechanism of noise generation in the vicinity of the car

Generally, the major source of noise is pressure fluctuation. For this reason, the first step in this development was to study an external profile that minimized pressure fluctuations. Specifically, we studied the ideal flow line profile which caused the air striking the end of the air rectification cover at the top of the car to flow to the rear of the car while minimizing separation of the flow from the air rectification cover and the surface of the car, when the elevator was traveling at high speed. In the case of the conventional structure, the upper air rectification cover has a curved external profile and a horizontal end. In addition, the upper beams of the car frame protrude outward, so this structure tended to cause the air flow above the car to become turbulent. To overcome this, we studied the ideal outer profile focusing on optimizing the flow line profile at the end of the air rectification cover, and also on minimizing the protrusions around the car.

3.2 Searching for sources of noise around the car

There are many large and small protrusions around the elevator car. While the elevator is traveling, the air flowing around the car separates at these pro-
trusions, resulting in the formation of vortices. At these points, large pressure fluctuations occur, which act as noise sources. To prevent this, it was necessary to determine the points that constituted major sources of noise, and to devise countermeasures in advance. The points where there were large fluctuations of pressure acting on the air flowing around the car were found by numerical fluid simulation, and the noise level in the vicinity of these places was verified by wind tunnel tests on a scale model of the elevator car. The results showed that the major noise sources in the vicinity of the car were located near the active roller guide installed at the top end of the car.

3.3 Reduction of noise around the car

As mentioned above, the main method of reducing noise generated around the car is to install streamlined air rectification covers for correcting the airflow, so the streamlined shape was optimized. In addition, countermeasures for the vicinity of the active roller guide, which was found to be a source of noise in the ultra-high-speed region, were also studied. Numerical fluid simulation was used to study the streamlined profile of the air rectification covers, and several patterns of car profiles with air rectification covers of different lengths, different end profiles and different radii of curvature were created and used to perform calculations (Fig. 3).

As a result, it was found that the maximum air correction effect was obtained by covering the equipment at the top of the car, including the upper beams protruding from the top of the car frame, with an air rectification cover. Also, in order to disperse the pressure acting on the end of the air rectification cover, the end of the cover was changed to a sharp edge. As a result, it was necessary to make the air rectification cover longer than that of the conventional structure, and the ideal streamlined profile was determined. Also, as a countermeasure for noise in the vicinity of the active roller guide, a small active roller guide cover for the equipment at the top of the car was newly developed. By adding the upper air rectification cover to the active roller guide cover, the air flow in the vicinity of the moving active roller guide is efficiently directed to the rear, thus eliminating noise sources.

From the above, the outer shape of the air rectification cover was optimized and also countermeasures against noise sources in the vicinity of the car were implemented, resulting in the super-streamlined profile shown in Fig. 4. By covering the equipment at the top of the car with an air rectification cover shaped so as to minimize protruding parts, and by combining the new active roller guide cover with the upper air rectification cover, the ideal streamlined shape around the car was obtained. This is the main feature of this structure. The optimized air rectification cover is about 1.4 times longer than the conventional structure, thus significantly reducing pressure fluctuations around the car.

3.4 Development of a soundproof car interior

The riding comfort of passengers in an elevator (noise inside the car) traveling at high speed is greatly affected by the extent to which noise can be prevented from entering the car. One solution is to use technologies for improving the soundproofing of the car. Because external noise increases in proportion to the speed of the car, an ultra-high-speed elevator requires even better soundproofing. Generally, in order to improve the soundproofing of the car, it is necessary to increase the weight of the car by using thicker structural members. However, this adversely affects the elevator system and cannot easily be used. To overcome this problem, we focused on the distance between the two sheets (air gap) comprising the double-walled structure of the car interior wall, and studied ways to improve the soundproofing by increasing this air gap. As a result, we succeeded in improving the soundproofing performance of the car without increasing its weight. In addition to the improved soundproof performance of the car interior walls, the airtightness around the car doors has been enhanced compared with the conventional structure, resulting in im-
proved soundproofing of the entire interior. An evaluation of the car interior of an actual elevator employing this structure was carried out, and the results showed that the target noise value for 1,080 m/min was attained.

4. Mitigation of Sensation of Compression in the Ears

In the case of an elevator intended for an ultra-high-rise building or tower, it is not possible to ignore the unpleasant sensation in the ears, or “sensation of compression,” which occurs when a person is riding the elevator. This unpleasant sensation in the ears occurs when the eardrum expands due to a difference between the outside pressure and the pressure in the middle ear, as a result of fluctuations in the surrounding pressure. Because an elevator moves in the vertical direction, the sensation of compression in the ears occurs due to the pressure difference arising from the change in altitude when the elevator is ascending or descending (for example, for a building that is 500 m tall, the pressure difference between the top and bottom floors is about 6,000 Pa). Because this sensation occurs due to the difference in atmospheric pressure, it depends greatly on the lift of the elevator (the height of the building), yet it is not possible to eliminate it completely. Accordingly, in order to reduce this unpleasant sensation even a little, a method of controlling the pressure change (atmospheric pressure change lines) inside the elevator car was independently developed. Also, an atmospheric pressure control unit which controls the pressure inside the car along these pressure change lines was newly developed, and was refined to the stage of commercial production to mitigate the sensation of compression in the ears.

5. Conclusion

This paper focused on riding comfort in ultra-high-speed elevators. It covered the suppression of car vibration, countermeasures for reducing noise in the car, and the development of measures for reducing the sensation of compression in the ears. The following conclusions were obtained.

To suppress vibration inside the car, an active roller guide for ultra-high-speed elevators was developed, thus attaining the same degree of riding comfort as by conventional active control.

To reduce noise inside the car, the shape of the air rectification cover was optimized, and noise reduction measures in the vicinity of the car and noise-proofing of the car itself were carried out, thus attaining the target noise value at a speed of 1,080 m/min.

To mitigate the sensation of compression in the ears experienced by passengers, air pressure change lines and an atmospheric pressure control unit were developed and commercialized.

References
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