Development of Train Nose Shape for Reducing Micro-pressure Waves

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To ensure that the micro-pressure waves generated during high speed running are reduced below the current level, and to reduce additional installation of wayside equipment, we have developed the nose shape of the Shinkansen. First, we obtained nose shapes by simulations for a tunnel without a hood, and verified the performances of those shapes by model experiments for tunnels with a hood. Second, we adopted a method of simulations for tunnels with a hood for more efficient development. The result was that the maximum speed would be increased to approximately 290km per hour by improving the nose shape with 9.1 meters nose length, which is equal to that of Series E2 (The nose length means the length of the leading car where the sectional area is subjected to changes). Additionally, we obtained the result that the speed would be increased to approximately 300km with 13meters nose length and approximately 320km per hour with 24meters nose length.

● Keyword：Micro-pressure wave, Compression wave, Hood

1 Introduction

When a high-speed train enters a tunnel, a compression wave is generated and travels through the tunnel at sonic speeds. When the wave reaches the exit, the compression wave is radiated as impulsive wave. This is called a micro-pressure wave (See Fig. 1) and causes noise and vibration problems.

There are two countermeasures for reducing this micro-pressure wave; (1) wayside measures including a hood at the tunnel entrance (a hood installed at the tunnel entrance on the train incoming side, and the cross-sectional area is 1.4 times the area of the tunnel, as seen in Fig. 2. It has air vents on its side. (2) measures for trains such as reduction of the car cross-sectional area and extension of the nose length.

We have adopted measures for trains to reduce the micro-pressure wave by improving the nose shape of the car.

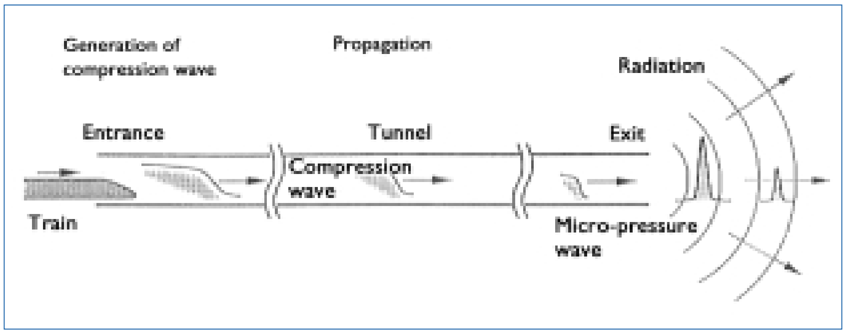

Fig. 1 Tunnel micro-pressure wave [1]

2 Method for reducing micro-pressure wave and approach to development

The micro-pressure wave increases with the rate of change of the compression wave, the pressure gradient (dP/dt). The countermeasures for trains have the effect of reducing the pressure gradient at the tunnel entrance. The following methods are available:

(1) Reduce the car cross-sectional area.

(2) Increase the train nose length.

(3) Optimize the train nose shape

Methods (1) and (2) are subject to restrictions due to comfort in the passenger car, passenger capacity, and so on. In the initial phase of development, we determined nose shapes considering the restriction of the nose length and the cross-sectional area of the car body by numerical fluid simulations for a tunnel without a hood. The effect of the nose shapes for tunnel with a hood was evaluated in the model experiment. The car model is an axially symmetric model, and the

Fig. 2 Hood at tunnel entrance

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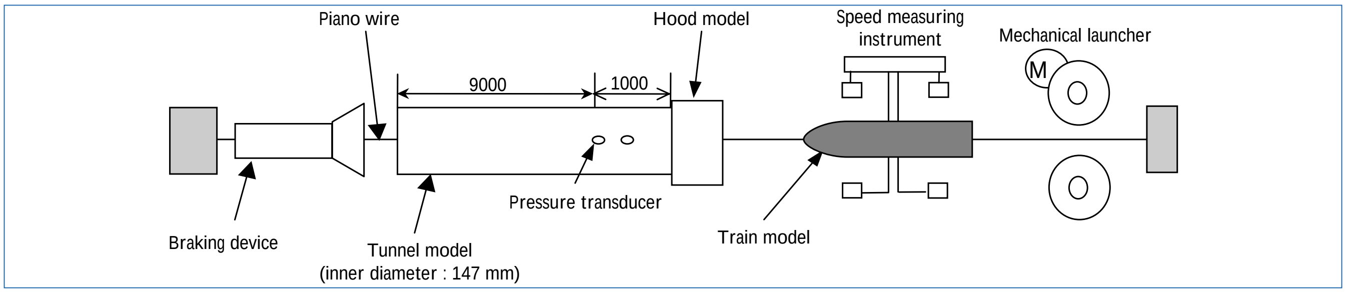

Fig. 3 Equipment of model experiment (a 1/61 scale model)

hood is shaped in a rectangular form with air vents on the top surface (Fig. 3). The maximum value of the pressure gradient of the compression wave at about 60 meters as a real scale from the tunnel entrance was used as the assessment index of the micro-pressure wave.

The basic relationship between the nose shape and pressure gradient[1] is shown in Fig. 4, where we can see that there is a difference in the maximum value of the pressure gradient according to the nose shape, even if the nose length and cross-sectional area of the car are the same. Thus, we have to optimize the nose shape. Further, the test result indicates that, when there is a large rate of change in the cross-sectional area of the car, the compression wave is also subjected to a sudden change, which means that the pressure gradient is the maximum. Accordingly, the constant rate of change such as the paraboloid of revolution in the cross-sectional area of the car is more effective for reducing the micro- pressure wave. Maeda[2] proposes an effective nose shape in reducing the micro-pressure wave, and this profile is shown in Fig. 5. It has the constant rate of change in the cross-sectional area except for the front end of the nose.

However, the actual configuration of a car requires consideration about restrictive conditions of the car such as securing the space for a separation/combination device. Considering the specifications of the Shinkansen trains introduced so far, we produced various leading profiles with the cross-sectional area of the Shinkansen trains ranging from 11.2 m^2 to 9.7 m^2 and the nose shapes ranging from 16 to 10 meters, and these shapes are put to simulation tests.

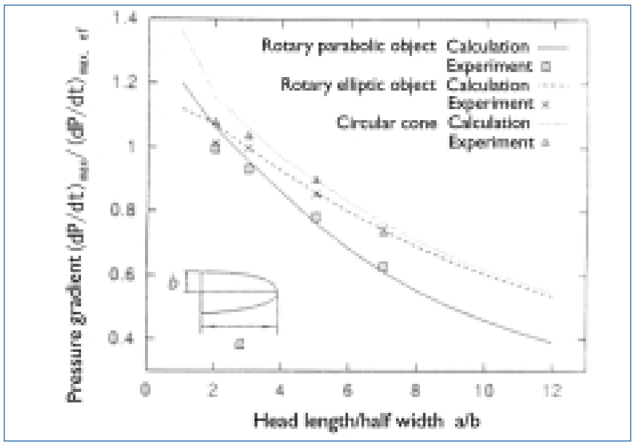

Fig. 4 Relationship between basic nose shape and pressure gradient [1]

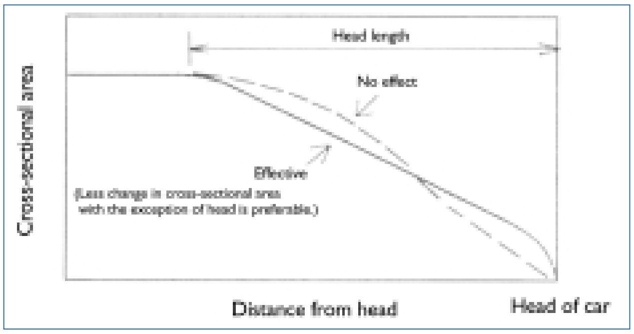

Fig. 5 Effect of nose shape in reducing micro-pressure wave in a tunnel without a hood

3 Simulation in a tunnel without a hood

3.1 Concept of nose shapes plan

(1) Cross sectional area of a car

A small cross-sectional area is effective in reducing the micro-pressure wave. But an excessively small cross-sectional area is not preferred because it may not satisfy sufficient passenger space. To work out the nose shape plan, we have adopted the cross-sectional areas for Series E2 (11.2 m^2), STAR21 (9.7 m^2) and JR West Series 500[3] (10.2 m^2).

(2) Ensuring the driver's cab space required for train nose

The nose shapes were configured so that the driver's cab space could be ensured. Some noses were designed on the basis of the Series E2, having the same cross-sectional profiles except for the portions within 4 meters from the front end of the nose. In case that the nose shape was reduced cross-sectional area, that the rate of change in the cross-sectional area remained the same.

(3) Practicable train nose length

Increased train nose is effective in reducing the micro-pressure wave, but space utility for the passenger room will be reduced. Then we used a length of up to 20 meters.

3.2 Outline overview of simulation

This simulation is intended to calculate the pressure level of the compression wave generated when the model for an axially symmetric nose shape of the train has entered the tunnel, as shown in Fig. 6.

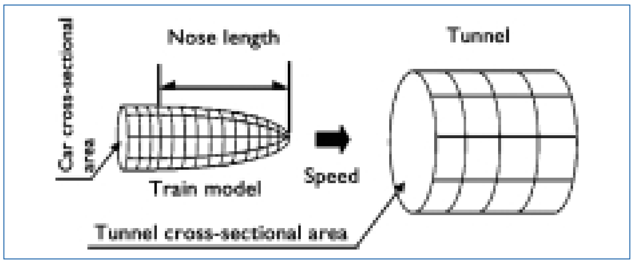

Fig. 6 Schematic Illustration of simulation

Calculation is performed according to the flow shown in Fig. 7. If the change in the cross-sectional area of the car is input, it is possible to get the compression wave and pressure gradient waveform when the model has entered the tunnel.

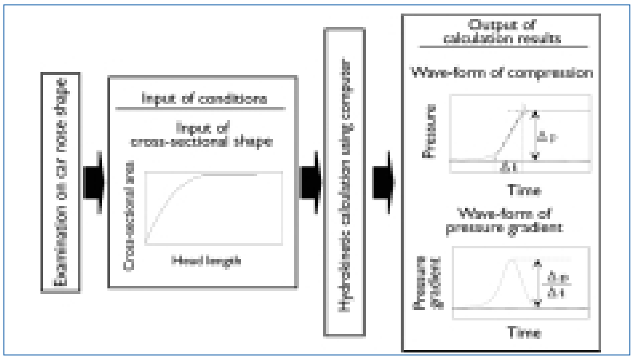

Fig. 7 Flow of simulation

3.3 Conversion from pressure gradient value to the speed for the evaluation

The speed used in the evaluation of the nose shape is obtained as follows:

The pressure gradient of Series E2 at 275 km per hour is used as a reference value. The pressure gradient of each nose shape is obtained as the reduction ratio of the reference value. Since the comparison with the reduction ratio of the pressure gradient is difficult to understand, the rate is further converted into the train speed.

Since the reduction ratio of the pressure gradient is proportional to a third power of the train entrance speed, the speed reduction ration is obtained, and the equivalent speed (the speed becoming the same pressure gradient as in Series E2 at 275 km per hour) is obtained from this speed reduction ratio and the reduction ratio of 275 km per hour in Series E2.

3.4 Target speed in this simulation

Actually, the wavefront form of the compression wave becomes gradually steeper during the propagation through the tunnel, so the maximum values of the pressure gradient at the entrance and exit are different. Especially in a long tunnel, the maximum value at the exit will be larger than that at the entrance.

Further, with a hood at the entrance, it is difficult to predict the pressure gradient on the exit side, because there are so many factors such as the length of the hood, the position and area of the air vents, the nose shape of the incoming train and many others.

For these reasons, our target speed was set at 325km per hour with some margin so that the maximum pressure gradient level at 300km per hour would be lower than the level of Series E2 at 275 km per hour.

3.5 Result of simulation

Based on the result of the simulations, we selected two of the most effective nose shapes (Fig. 8) meeting the target speed, which length is within 12 meters. These designs were used to conduct a model experiment.

4 Model experiments (Part 1)

Two profiles (Fig. 8), worked out on the result of the simulation of the tunnel without a hood, were put to the model experiments for the tunnel provided with a hood. We obtained the speed where the maximum pressure gradient is the same as in Series E2 at 275 km per hour (Table 2). The lengths of the hood were set to four types; 10, 17, 25 and 30 meters, which were the typical lengths of existing hoods.

As a result, in profile No. 2, the speed of the test profile generating the same micro-pressure wave as in Series E2 at 275 km per hour was 281 to 293 km per hour at the optimum air vents for Series E2 (current conditions on wayside equipment). Further, the speed of the test profile generating the micro-pressure wave equivalent to Series E2 at 275 km per hour was 293 to 312 km per hour, when the vents were adjusted (improvement of the wayside equipment) to the test profile. When the hood length was 17 or 25 meters, the speed exceeded 300 km per hour. When the hood length was 10 or 30 meters, the speed did not reach 300 km per hour. So we worked out several proposals on the nose shape to carry out additional experiments.

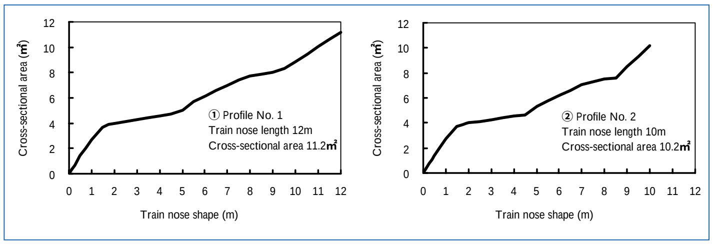

Fig. 8 Profiles No. 1 and 2

Table 2 Result of model experiments (Part 1)

Model		Type E2(km/h)	No1(km/h)	No2(km/h)
Without hood		275	325	328
Optimum vents, Series E2	10m	275	283	293
	17m	275	268	285
	25m	275	269	284
	30m	275	274	281
Optimum vents for each various profile	10m	*(275)	*(283)	*(293)
	17m	269**	297	312
	25m	262**	286	301
	30m	263**	282	294

* Could not find out the optimum vents for each various profile
** At at the optimum vents for profile No. 2

5 Model experiments (Part 2)

The following shows the nose shape plans used in the experiment:

(1) Model plans profile that partially had some nose profiles as the Series E2 since the current hood has an vents adjusted for Series E2 (Fig. 9). There were two profiles and selected from the simulation results.

(2) Model plans with some profiles as the Series E2 b/w the edge and the point which is 1 meter behind the edge and same rate of cross-sectional area changes as the Series E2 behind the point 1 meter behind the edge. These models were able to be applied to the train which had different cross-sectional area or different nose length from Series E2. (Fig. 10)

(3) A model plan with 10 meter nose length and 10.7square meter cross-sectional area. The rate of cross-sectional area change was same as the Series E2 partially that the connector was installed, and intermediate b/w Series E2 and linear shape model at the other part.

The values of nose length and cross-sectional area were selected from the simulation result which realizes 300km per hour for the tunnel without a hood. There was no nose shape to exceed 300 km per hour by the experiment for hood with vents optimized for Series E2.

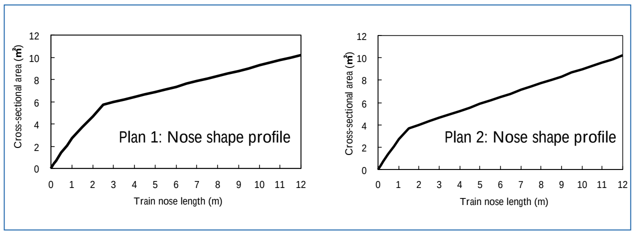

Fig. 9 Plans 1 and 2

Model specifications (converted into actual specifications)

[1] Plan 1. Cross sectional area: 10.2 m^2; Train nose length: 12 m
(The cross-sectional area of Series E2 is used up to 2.5 meters)

[2] Plan 2. Cross sectional area: 10.2 m^2; Train nose length: 12 m
(The cross-sectional area of Series E2 is used up to 1.5 meters)

[3] Plan 3. Cross sectional area: 10.7 m^2; Train nose length: 12 m
(Change of the cross-sectional area of Series E2 is used up to 1.0 meters)

[4] Plan 4. Cross sectional area: 10.7 m^2; Train nose length: 10 m
(Change of the cross-sectional area of Series E2 is used up to 1.0 meters)

[5] Plan 5. Cross sectional area: 10.7 m^2; Train nose length: 8.5 m
(Change of the cross-sectional area of Series E2 is used up to 1.0 meters)

[6] Plan 6. Cross sectional area: 11.2 m^2; Train nose length: 12 m
(Change of the cross-sectional area of Series E2 is used up to 1.0 meters)

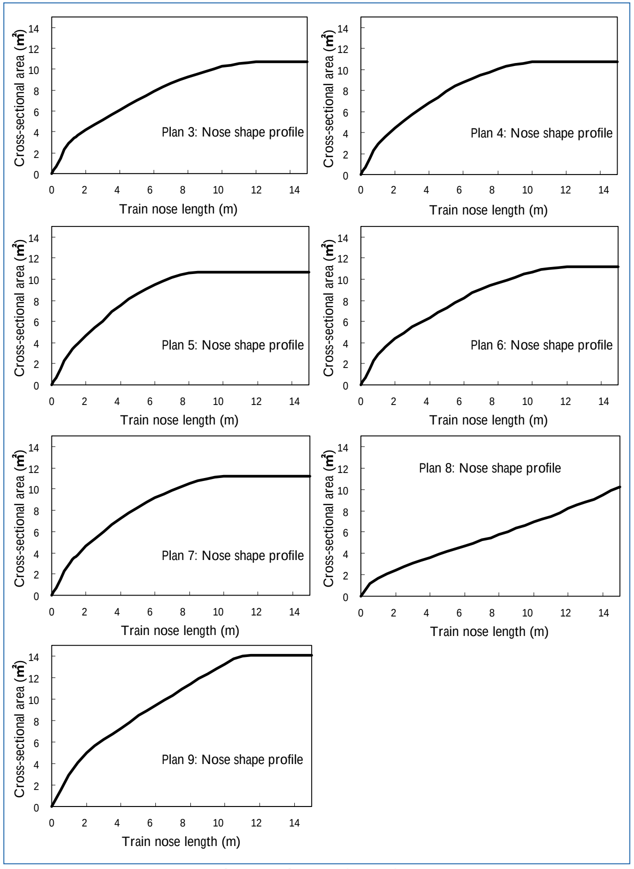

Fig. 10 Plans 3 through 9

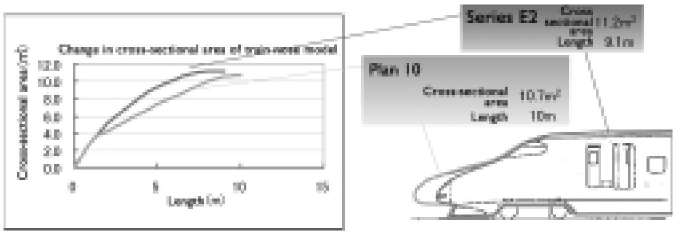

Fig. 11 Plan 10

Table 4 Results of model experiments (Part 2) -1

		Series E2 (km/h)	PLAN1 (km/h)	PLAN2 (km/h)	PLAN3 (km/h)	PLAN4 (km/h)
Without hood		275	313	330	308	296
Optimum vents, Series E2	10m	275	292	297	289	285
	17m	275	284	285	286	282
	25m	275	283	283	277	279
	30m	275	282	285	280	280
		PLAN5 (km/h)	PLAN6 (km/h)	PLAN7 (km/h)	PLAN8 (km/h)	PLAN9 (km/h)
Without hood		285	301	290	351	279
Optimum vents, Series E2	10m	285	279	281	301	249
	17m	285	278	281	283	249
	25m	281	275	278	283	249
	30m	284	277	276	282	248

[7] Plan 7. Cross sectional area: 11.2 m^2; Train nose length: 10 m (Change of the cross-sectional area of Series E2 is used up to 1.0 meters)

[8] Plan 8. Cross sectional area: 10.2 m^2; Train nose length: 15 m (The micro-pressure wave is the minimum without hood)

[9] Plan 9. Cross sectional area: 14.07 m^2; Train nose length: 11.5 m (Nose shape of Series E4)

Table 4 Results of model experiments (Part 2) -2

		Series E2	Plan10	
		Pressure gradient (**k**Pa/s) 275km/h	Pressure gradient (**k**Pa/s) 300km/h	Speed equivalent to the current (km/h)
Without hood		736	701	305
Optimum vents, Series E2	10m	400	498	279
	17m	345	375	292
	25m	295	338	287
	30m	270	295	291

6 Simulation in the tunnel with hood

Various types of train nose shapes were put to model experiments. The speed realizing some micro-pressure level as Series E2 (275km per hour) were lower than 300 km per hour in all nose shapes.

Conventionally, the performances of the nose shapes selected from the results of simulations without a hood were verified in model experiments in the tunnel with a hood. Since numerical fluid simulation(hereinafter referred to as "CFD") with the hood has become available due to the recent improvement in the performances of the supercomputer, we decided to develop the train nose shape that permitted traveling at 300 km per hour under the current hood condition by the axially symmetric CFD.

When the Series E2 traveled at 320 km per hour, the maximum pressure gradient at the tunnel entrance was approximately 1.6 times of that at 275 km per hour. So the target level was set in such a way that the maximum pressure gradient at the tunnel entrance was reduced about 40 percent (from the level of Series E2).

6.1 Axially symmetric CFD analysis

(1) Analysis conditions

The following describes the conditions of the hood and car for analysis:

[1] Four conditions shown in Table 5 were mainly used for the hood.

Table 5 Conditions for hood

No.	Cross sectional area ratio between hood and tunnel	Length of hood **m**	Area of vents **m^2**
1	1.4	10	5.9
2	1.4	17	10.6
3	1.4	25	15.2
4	1.4	30	14.0

[2] The cross-sectional area of the car was 11.2 m^2.

[3] Four train nose lengths of 9.1(equal to the nose length of Series E2), 10, 13 and 16 meters were used.

(2) Analysis method

Basic equation: Euler equations (compressible flow of in viscid fluid)

Analysis method:

TVD scheme, finite volumes method and structured grids (3rd-order MUSCL method and Roe's approximation)

Time integration: Explicit difference

(3) Assessment index

Assessment index was set to the maximum pressure gradient at 60 meters from the tunnel entrance when the train enters the tunnel.

6.2 Modeling the hood

On axially symmetric CFD, it is very important to model the three-dimensional hood structure. Comparison was made with the result of the model experiment, using a slit model provided with slits having the same area as the area of the real vents over the circumference of the tunnel model. The comparison result revealed that the phenomenon could not be reproduced effectively. To solve this problem, a new double circular tube model (Fig. 13) was invented.

This was composed as follows: The hood was modeled as a circular tube, and a circular tube (outer circular tube) was provided outside the circular tube (inner circular tube) having an opening slits, and the clearance between the outer and inner circular tubes matches the area of the real vents. Although there was a slight difference from the model experiments, we decided to use it as a hood model.

Fig. 14 shows the result of a model experiment with a 10-meter hood and axially symmetric CFD, using a slit model and double circular tube model. The result of the model experiment showed that the waveform contained two peaks. Since the slit model generated one-peak waveform, it was found to be inappropriate as a hood model. On the other hand, since the double circular tube model exhibited a two-peak waveform, which represented the phenomenon, it was considered an appropriate hood model.

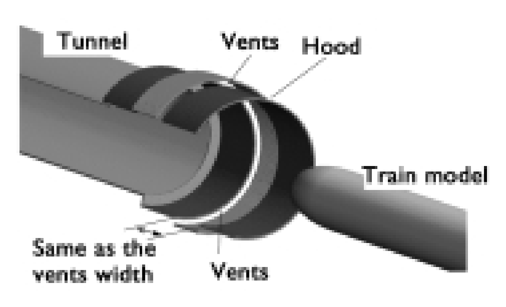

Fig. 13 Double circular tube model

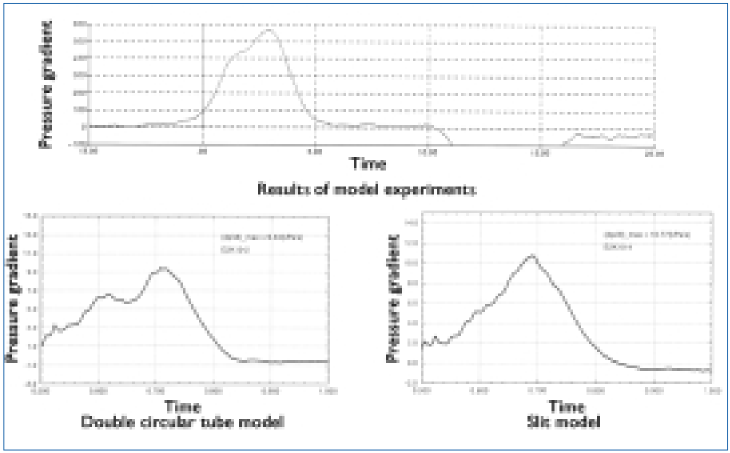

Fig. 14 Comparison between model test results and axially symmetric CFD analysis results (slit model and double circular tube model)

6.3 Optimization procedure of train nose shape

The nose shape of was configured in three basic forms; ellipsoid of revolution, paraboloid of revolution and cone (Fig. 15). The maximum value of the pressure gradient was the smallest for the paraboloid of revolution when the train entered the tunnel without a hood [2]. And even if the front end was cut off, the pressure gradient remained unchanged [2]. Thus, we optimized the nose shape, using the shape formed by connecting two to four polygonal lines based on the linear change of the paraboloid of revolution (hereinafter referred to as "2- to 4-step paraboloid of revolution").

For example, a 1st /2nd step connection point, namely, the optimum point where two lines bend is obtained in the two-step paraboloid of revolution. Fig. 16 shows the connection points that the parameter study was made. Calculation was made on these twenty points, namely, twenty nose shapes. Then a similar calculation was made by changing the following conditions for the hood. The optimum connection point may be slightly different depending on the length of the hood. Of all hood lengths, better one on an average was adopted as the optimum nose shape.

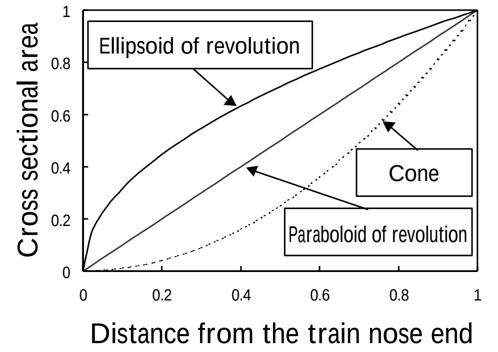

Fig. 15 Three basic forms

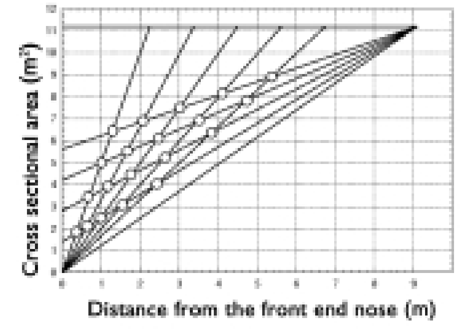

Fig. 16 Connection points between two-step paraboloid of revolution

6.4 Result of analysis

Fig. 17 shows the result of analyzing the two-step paraboloid of revolution having a nose shape length of 9.1 meters. Fig. 18 shows the changes in cross-sectional areas of the optimum two-step paraboloid of revolution and the optimum four-step paraboloid of revolution having a nose shape length of 9.1 meters. The optimum two-step paraboloid of revolution is formed in such a way that the cross-sectional area of Series E2 is cut away on the portion about two meters back from the front end. Further, when optimization was made for the four-step paraboloid revolution, the pressure gradient was a little more reduced than that in the case of the two-step paraboloid revolution. So this optimum four-step paraboloid of revolution was determined as the optimum nose shape having a nose length of 9.1 meters.

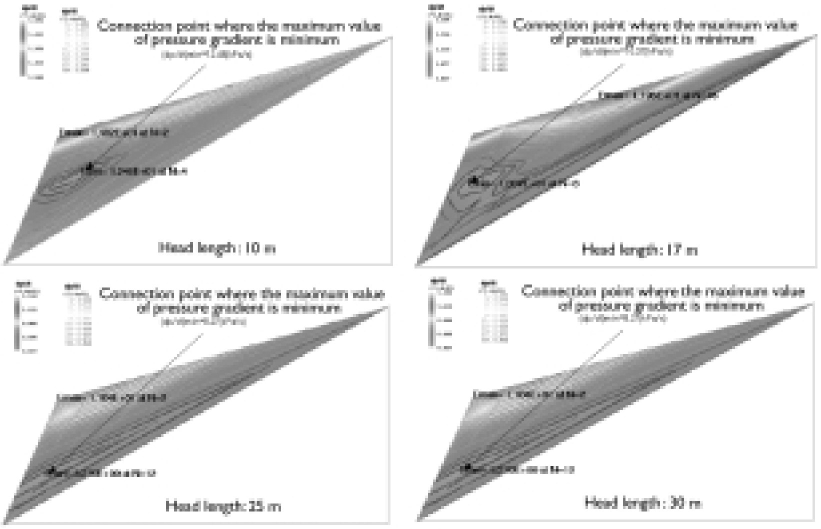

Fig. 17 Optimization of the change in cross-sectional area due to two-step paraboloid of revolution (for a nose shape length of 9.1 meters) (The maximum pressure gradient is indicated by a contour line).

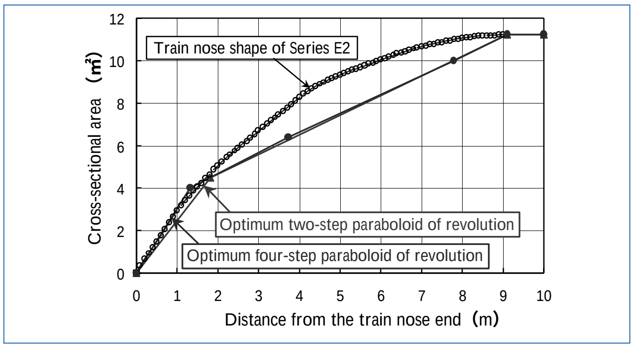

Fig. 18 Optimum train nose shape having a nose length of 9.1 meters

Fig. 19 shows the change in cross-sectional area of the optimum nose shape for each nose length. Fig. 20 shows the valve of the maximum pressure gradient with reference to the value for Series E2 represented as 100%.

As a result, it has been revealed that the pressure gradient can be reduced about 15% from the level of the Series E2 with the nose length is 9.1 meters, and about 22% from the level of the Series E2 with the nose length is 13 meters. Though the target reduction of 40% could not be achieved even when the leading length was 16 meters, it has been made clear that the target reduction can be achieved when the train nose is increased to 24 meters, except for the hood of 30 meters.

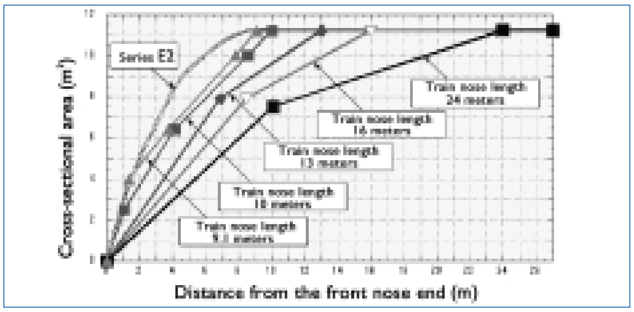

Fig. 19 Optimum profile for each nose length.

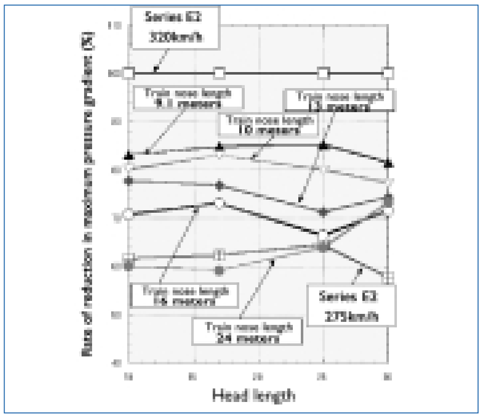

Fig. 20 Pressure gradient of the optimum profile for each nose length.

6.5 Result of axially symmetric CFD

Axially symmetric CFD has clarified the following points:

(1) The micro-pressure wave can be reduced approximately 15% from the level of Series E2 by appropriate modification of changes in cross-sectional area at the same nose length of 9.1 meters as that of the Series E2. (About 290 km per hour is the speed where the micro-pressure wave is equal to that at 275 km per hour in the Series E2.)

(2) If the nose length is increased to 13 meters, reduction of the micro pressure wave level can be more than 20% from the level of Series E2. (About 300 km per hour is the speed where the micro-pressure wave is equal to that of the Series E2 at 275 km per hour.)

(3) If the nose length is increased to 24 meters, reduction of the micro pressure wave level can be 40% from the level of Series E2 except for the case with 30-meter hood. (About 320 km per hour is the speed where the micro-pressure wave is equal to that at 275 km per hour in the Series 2E.)

7 Issues to be solved

We have succeeded in obtaining the optimum change in the cross-sectional area by the axial symmetric CFD. The next step is to develop a 3-D train nose shape which meets the optional change in cross-sectional area with consideration of the configuration of the driver's cabin space and so on.

For further speed-up, it is necessary to examine the best combination of countermeasures for the entrance side such as optimizations of the train nose shape, hood specification and compression wave propagation process.

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