EXPERIMENTAL AND NUMERICAL STUDIES ON ULTRAHIGH-SPEED ELEVATORS

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ABSTRACT

Recently in Japan there has been an upsurge in the construction rush of multistoried buildings due to concentration of population in big cities, especially in the Tokyo metropolitan area. This has been exacerbated by the tremendous increase of land prices. This has accelerated demand for elevators of a higher speed and better performance. To meet this demand, many technical problems which did not exist with the traditional type of elevators must be solved. One of these problems is aerodynamic sound. This paper introduces fundamental experiments and numerical simulations for suppression of aerodynamic noise around the elevator car generated by air flow and improved sound isolation inside it.

1. ANALYSIS OF AIR FLOW AROUND THE CAR (analysis of traditional-type car) (why is more noise generated in a downward-running car than that in an upward-running car?)

Measurement of air speed around an actual traditional-type car (Fig.1) has been conducted as one researches areas for reduction of inside-car noise during high-speed running. This has revealed that inside-car noise during downward running is 2 to 4 dB(A) larger than during upward running. Furthermore an accelerated flow 1.3 times the running speed is generated in the area in front of the door only during downward running.

Since the door and its surrounding area have less transmission loss, as described later, it is important to clarify the reason why this accelerated flow is generated to devise measures to minimize noise.

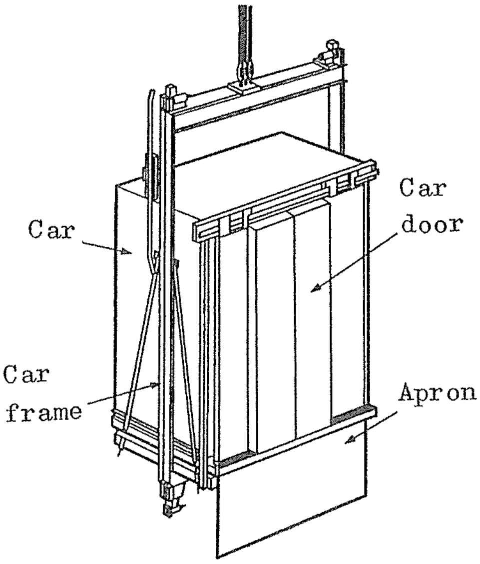


Fig. 1 Schematic diagram of elevator

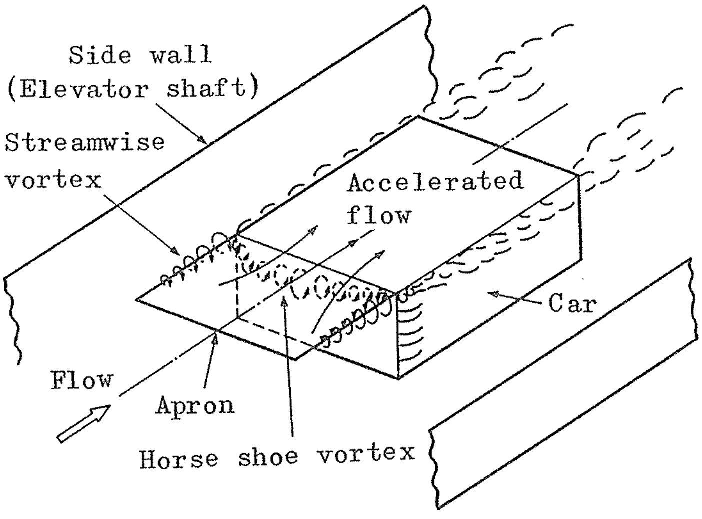


Fig. 2 Flow around apron during downward motion of car

Generally, inside-car noise is greater during downward running than during upward running. Nakajima presumed that this is caused by upward flow (chimney effect) produced in the hoistway . However, since no upward flow was observed in this experiment, the accelerated flow during downward running is presumed to be strongly affected by the presence or the shape of the apron. This was investigated by simulating the air flow around the model.

1.1 Experiment (Visualizing experiment in water tank)

A water tank was used first to observe the overall flow and to visualize the flow around the model submerged in water using a tracer. The Re number based on the car width and the main stream speed is approximately 800. This value is approximately 4 powers of 10 smaller than value for the actual car but it is presumed that the fundamental influence of the apron could be observed.

The model was placed in the water with the front of the car (door side) up and the free surface simulating the moving wall. Observation of the flow clealy showed that large-scale horse-shoe-shaped vortices were produced at the rear of the apron and the lower corners of the car, as well as streamwise vortices accompanied by flows coming around from the rear of the apron to the front at both ends of the apron, as shown in Fig.2. These streamwise vortices presumably converge at the center of the car-door side resulting in accelerated flow. High-pressure fluid on the rear of the apron due to stagnated flow will generate a vortex by moving around to the relatively low pressure side of the apron surface.

1.2 Numerical Analysis

In an actual elevator, the car runs relative to the hoistway wall. To observe the influence by moving a wall, not possible in experiments, a numerical simulation for the flow around the elevator car was carried out. An Re number of 1.3×10^5 was assumed. Fig.3 shows stream lines around the car. The near side in the figure is the door side and apron is positioned on the left side. The left side of the figure corresponds to the car's lower part and the right side to the car's upper part. The flow comes from the right and we can observe the flow lines in front of the car door converging to the center. It is evident that the flow in front of the door

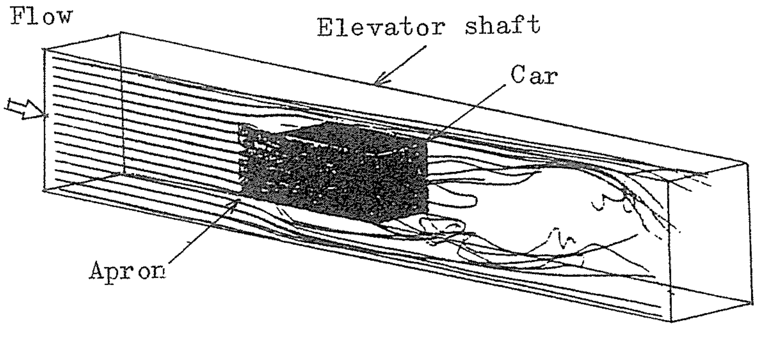


Fig. 3 Streamline around elevator model

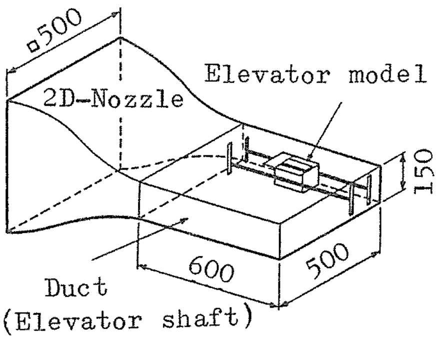


Fig. 4 Wind tunnel experimental setup

is accelerated by the effect of the apron. Even when considering a moving wall similar to the actual elevator, acceleration in front of the door was verified.

1.3 Summary

We examined the effect of an apron surrounding the elevator car during downward running through visualized experiments and numerical simulation. The results demonstrated that streamwise vortices are generated around the apron tips followed by an accelerated flow in the front of car.

Suppression of these streamwise vortices or, if they are generated, preventing an effect on the car front will presumably reduce the accelerated flow in front of the car in downward running with reduction of subsequent aerodynamic noise.

2. ANALYSIS OF FLOW AROUND THE CAR (Effect of aerodynamic cover)

Aerodynamic noise is a big problem in the automobile field and all makers are conducting studies to solve it. As a result of these studies, it has become clear that this type of aerodynamic noise has a strong correlation to pressure fluctuations on the wall boundary surface, and flow separation and reattachment phenomena play an important role in this mechanism causing noise.

Aerodynamic noise is greatly affected by air flow around a car. Experiments have been carried out in a wind tunnel facility with a scale model (approximately 1/20) simulating the basic shape of an actual elevator car (car, carframe, doors, and apron) to visually observe separation and reattachment phenomena around the model through an oil flow pattern method. At the same time, wall pressure fluctuation was measured to examine the effect of the shape of the apron (cover) on the flow around the car.

2.1 Experimental Setup

For the experiments, a blow-out type wind tunnel was used in which a duct was mounted to simulate the hoistway in the outlet of the nozzle. The experimental setup is shown in Fig.4. At the lower part of the model, an apron or an aerodynamic cover was fixed and on both sides rods imitating guide rails were mounted. On the model used for measuring wall pressure fluctuation, holes for mounting miniature pressure sensors were provided on six walls.

2.2 Experiment Method

Experiments were carried out assuming an Re number of 1.3 x 10 based on the main flow speed and the car width. Liquid paraffin was used as the base oil and titanium oxide was used as a pigment. A miniature pressure converter (EPI-080-2G, Entran Co. make) was used to measure pressure fluctuation. The diameter of the sensitive part was approximately 2 mm and the effective frequency range was 20 kHz. Frequency analysis was carried out on the output signal after being amplified 200 times with a dc amplifier. The analyzing range was 50 kHz with a frequency resolving power of 50 Hz at this time. The fluctuation from 50 Hz to 15 kHz was taken as the analyzing objective.

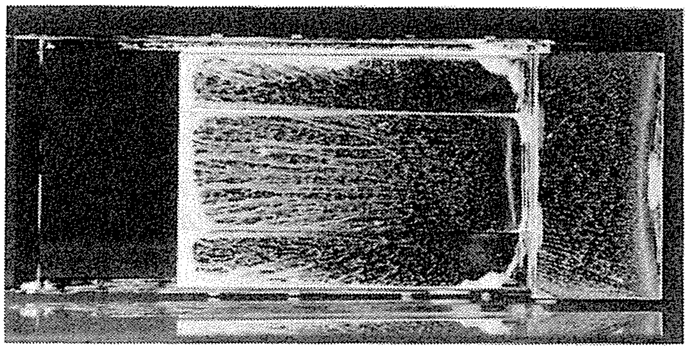
2.3 Experiment Results

(1) Effect of guide plate

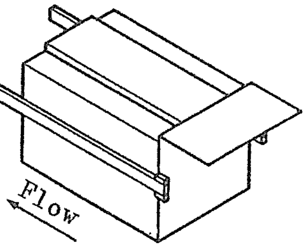
As described above, streamwise vortices were generated on the apron tips during downward running, due to a pressure difference between the front and rear of a thin plate apron, inducing accelerated flow in front of the door. Figs. 5 and 6 present the case for a traditional apron mounted and the case for guide plates provided at the apron tips, showing the oil flow pattern at the door side (a) and its interpretation (b) during downward running.

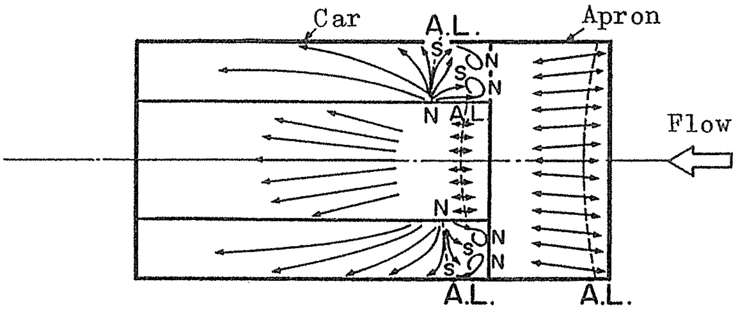
The letters S and N indicate the saddle point and the node point respectively, A.L. in the figure indicates reattachment lines assumed from the behavior of the oil agent and S.L. indicates flow separation lines. Observation of the traditional-type apron (Fig. 5 (a) and (b)) shows that the converged oil agent is cleared from the front half of the apron to the central part. This indicates accelerated flow in front of the door by streamwise vortices caused by a pressure difference between the front and rear of the apron. The white oil agent deposited on the front edge shows removal due to small speed. Also, clear reattachment lines are observed at the door pocket and the door at both sides of the car during downward running. We can observe formation of a back-step flow due to the door step irregularity during downward running.

In Fig. 6 (a) and (b) we can also observe the oil agent flowing parallel to the main flow without converging at the center. Suppression of accelerated flow in front of the door by preventing generation of rolled-in flow (streamwise vortices) at the apron tips is evident. For the apron provided



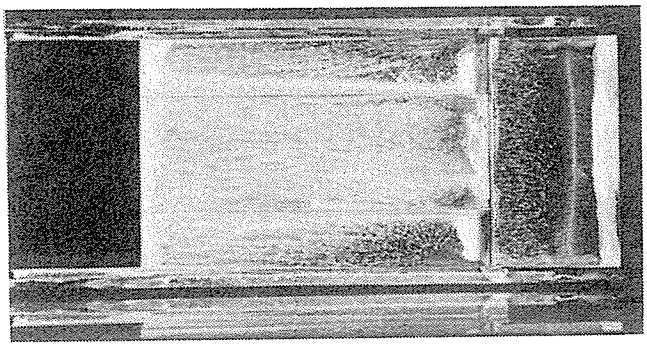
(a) Oil flow pattern



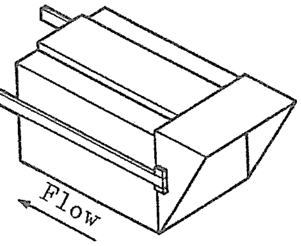


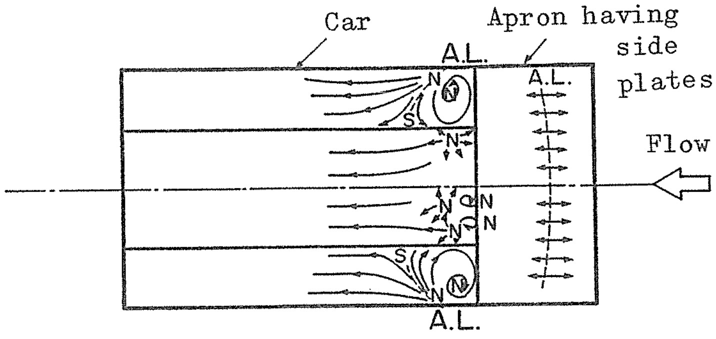
(b) Interpretation of the flow

Fig. 5 Flow around the model with a standard type apron (Front view) with guide plates, back-step flow also appears in front of the door, but wall pressure fluctuation is reduced by the amount of flow speed reduction.



(a) Oil flow pattern





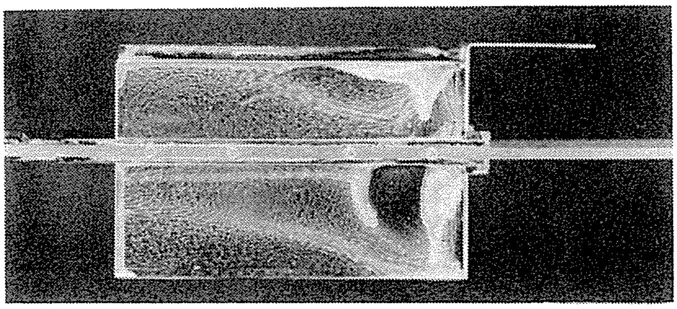
(b) Interpretation of the flow

Fig. 6 Flow around the model with an apron having a guide plate (Front view)

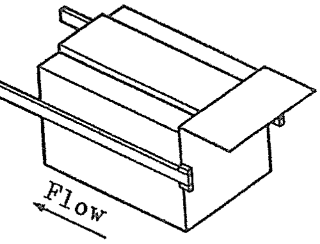
(2) Effect of aerodynamic cover

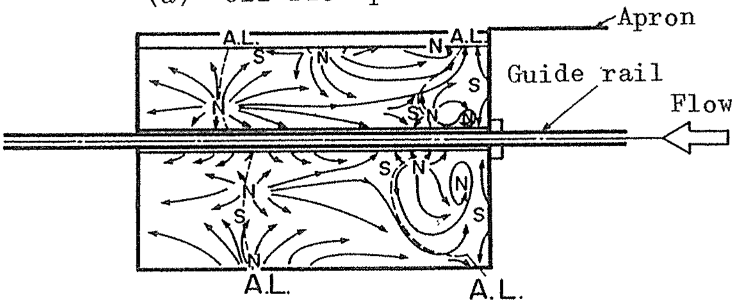
It was clear that an apron with guide plates could suppress accelerated flow in front of the door and reduce wall pressure fluctuation at the door side. Next we considered reducing wall pressure fluctuation on surroundings of the whole car. A big pressure fluctuation is generated in the vicinity of the reattachment region decorating the phenomena of flow separation and reattachment . it is important to prevent separation of flow to suppress such a pressure fluctuation. Figs. 7 and 8 (a),(b) and (c) present car side wall oil flow pattern (a) and its interpretation as well as wall pressure fluctuation distribution (c). The (c) figures show the wall pressure fluctuation size, described for the measuring point at the center, taking RMS values for the sum of pressure fluctuations in the range of 50 kHz to 15 kHz.

First described is the correspondence of oil flow pattern to wall surface fluctuation distribution. Comparing Fig. 7 (b) and (c) shows that the place with a big pressure fluctuation is at the node point (N) shown in Fig. (b) and is positioned in the vicinity of the node point (reattachment region) where oil agent is spreaded radially. A big pressure fluctuation is measured at the upper central part in the door side region (upper half of the figure) and at the region close to the right guide rail and the left central part of the figure in the rear side region (lower half of the figure). It was revealed that flow field interpretation and position

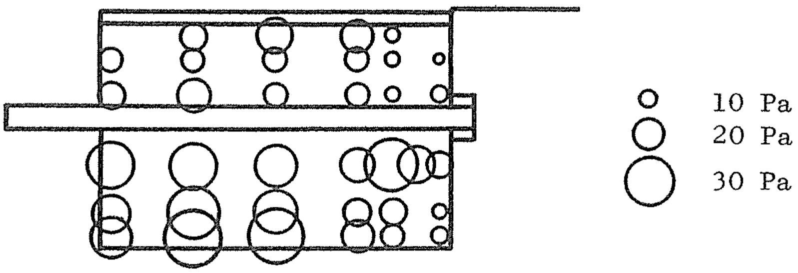


(a) Oil flow pattern





(b) Interpretation of the flow



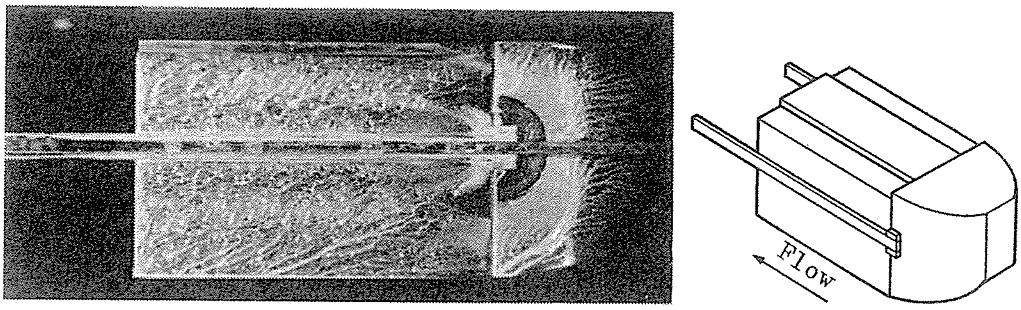
(c) Wall pressure fluctuation distribution

Fig. 7 Flow around the model with a standard type apron (Side view)

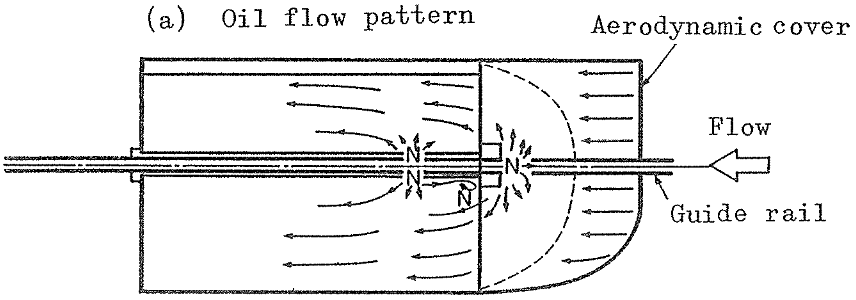
correspondence of wall surface fluctuation distribution are similar on other measuring surfaces, showing that a big pressure fluctuation is generated in the vicinity of the attachment node point.

As described avove, on the car side provided with a traditional-type apron, an extremely complex flow is generated by interference of separated flow at the lower side of the car with horse-shoe shaped vortices generated at the mounting point of apron, carframe and guide rail surrounding.

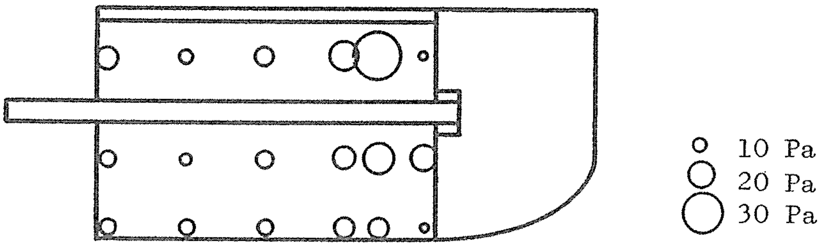
Contrary to the above, it is clear that the oil agent flows almost parallel to the main flow along the whole side surface when provided with an aerodynamic cover (Fig. 8 (a) and (b)). The flow is once separated at the cover center and then reattached while interfering with horse-shoe shaped vortices (black half-circle regions in the figure). At the top end of the carframe a clear node point is recognized. One pair of node points existing along the guide rails seems to be by the flow separated by the carframe. It is clear that mounting of a cover can suppress generation of a large scale separated flow, thus reducing wall pressure fluctuation on almost the whole side wall (Fig. c). The relatively big pressure fluctuation at the right of the figure in the door region is presumed to be caused by irregularity in mounting the cover.



(a) Oil flow pattern



(b) Interpretation of the flow



(c) Wall pressure fluctuation distribution

Fig. 8 Flow around the model with an aerodynamic cover (Side view)

2.4 Summary

We have carried out wind tunnel experiments using a scale model simulating the basic shape (including guide rails) of the elevator car to examine the effect of an apron provided with guide plates and of an aerodynamic cover. The result is as follows:

(1) Provision of guide plates at the apron side edges can suppress streamwise vortices, resulting in suppression of accelerated flow in front of the door during downward running.

(2) From the oil flow pattern information, a region with a big wall pressure fluctuation can be assumed. The flow field interpretation and wall pressure fluctuation distribution correspond well in postion, producing a big wall pressure fluctuation in the vicinity of the attachment node point.

(3) Mounting of an aerodynamic cover can reduce wall pressure fluctuation around the car.

3. SOUND INSULATION CHARACTERISTICS

Mounting of a rectification device (aerodynamic cover) can suppress sound generation, and improved sound insulation characteristics of the car can reduce inside-car noise.

3.1 Measurement of Transmission Loss by Sound Intensity Method

Sound isolation characteristics for a wall and other material is evaluated from the transmission loss. In the past, highly accurate measurement of transmission loss required measurement in a reverberation chamber comprised two interconnected rooms. However, by using the sound intensity method, the transmission loss of the car can be obtained with high accuracy without using a special laboratory. Fig. 9 shows the configuration of the measurement. By placing a sound source with a white noise character in the car, transmission loss can be obtained by measuring acoustic power transmitted to the outside of the car through the sound intensity method,

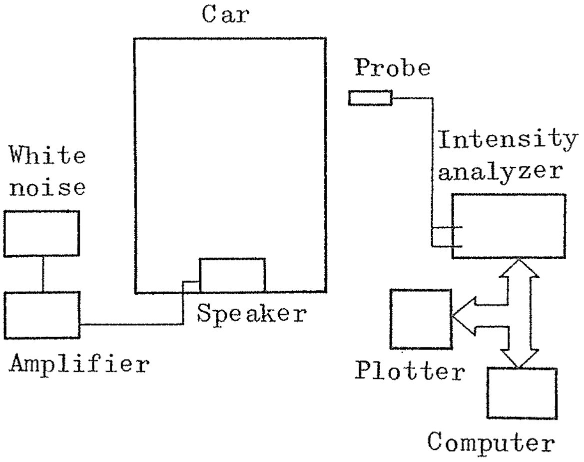


Fig. 9 Block diagram of measurement system

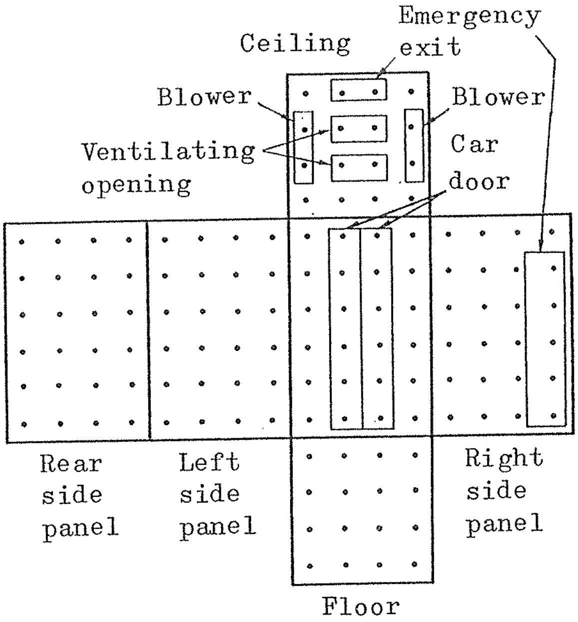


Fig. 10 Measured points on car surface

Assuming the car inside as a diffuse sound field, sound power W leaked to outside the car is shown by the following formula.

$$W = (C/4)\cdot E\cdot S\cdot \tau \quad (W) \qquad (1)$$

where, E: Average energy density in the car (W s/m)
τ: Overall transmission ratio
S: Total area of walls (m^2)
C: Sound velocity (m/s)

The relationship between sound pressure P in the internal sound field and energy density E is

$$E = \frac{P^2}{\rho C^2} \quad (W\cdot s/m^3) \qquad (2)$$

Where, ρ: Air density (kg/m^3)

From formulas (1) and (2), transmission loss TL is

$$TL = \overline{SPL} - PWL + 10\log_{10}S - 6.2 \ (dB) \qquad (3)$$

However, $TL = 10\log_{10} 1/\tau$ (dB)

Where, $\overline{SPL}$: Average sound pressure level in car

$$\overline{SPL} = 10\log_{10}\frac{P^2}{(2\times10^{-5})^2} \quad \text{(dB)}$$

PWL: Sound power level leaked to car outside

$$PWL = 10\log_{10}\frac{W}{10^{-12}} \quad \text{(dB)}$$

From formula (3), transmission loss can be obtained by measuring sound power level leaked to the outside. Sound power level PWL leaked to outside the car can be obtained by dividing the car once into 128 elements of 0.5 m x 0.5 m, as shown in Fig. 10, to measure the intensity in the vicinity of each element surface and then compose them. Thus sound power level per element is clarified, enabling measurement of transmission loss at each part of the car.

3.2 Measurement Result

Transmission loss obtained from formula (3) based on an actual measurement result is shown in Fig. 11. The figure shows comparison of transmission loss for each part such as car door surface, ceiling and each side wall aginst the overall transmission loss. From these figures, it is quantitatively clear that transmission loss through the ceiling is low in the low frequency area but the loss through the door surface is low in the high frequency area, such as 1600 Hz or more.

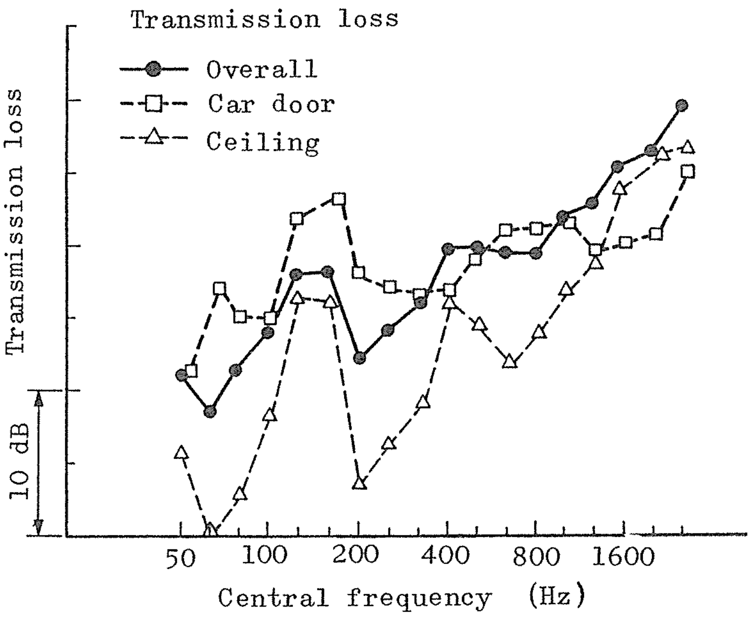
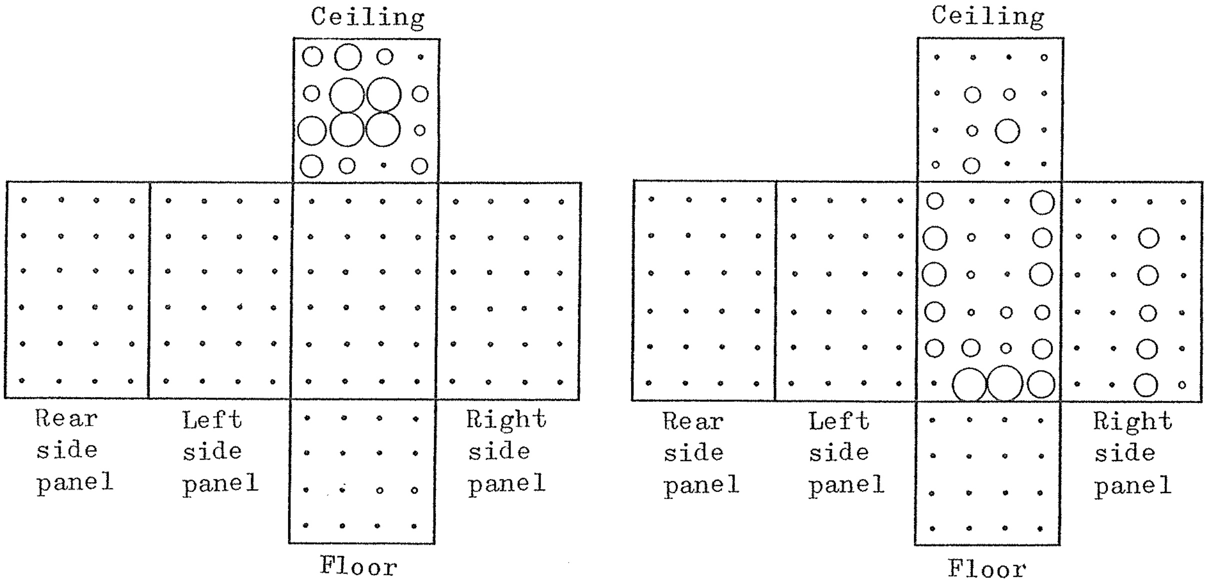


Fig. 11 Transmission loss of individual car surface

3.3 Summary

Intensity level of each element is mapped in Fig. 12. As an example, the 1/3 octave band with a central frequency of 80 Hz and 1600 Hz is shown. The figure shows the intensity level of each element by the area of a circle. Improved sound isolation characteristics for a larger circle will effectively enhance sound isolation characteristics of the entire car.



(a) Central frequency 80 Hz (b) Central frequency 1600 Hz

Fig. 12 Intensity map in car surface

4. CONCLUSION

By fundamental experiments and numerical simulation for aerodynamic noise suppression,we have obtained the following useful knowledge for car construction applicable to ultrahigh-speed elevators.

(1)The flow in front of the car is reduced and accelerated by the effect of the apron.
(2)Provision of guide plates on the apron's side edges can suppress this accelerated flow.
(3)Mounting of an aerodynamic cover can reduce wall pressure fluctuation around the car.
(4)The oil flow pattern information from wind tunnel experiments and wall pressure fluctuation correspond well.
(5)Transmission loss through the car's ceiling is low in the low frequency area but the loss through the door surface is low in the high frequency area.

BIOGRAPHICAL NOTES

N. Teshima received the M. S. degree in mechanical engineering from Tokyo University in 1967. He has been engaged in the development and design of elevators in Toshiba Corporation, where he studies the vibration of elevators and the problems of elevators during earthquake.
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