

# Unsteady Aerodynamic Response of a Vehicle by Natural Wind Generator of a Full-Scale Wind Tunnel

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## ABSTRACT

In recent years, the automotive manufacturers have been working to reduce fuel consumption in order to cut down on CO<sub>2</sub> emissions, promoting weight reduction as one of the fuel saving countermeasures. On the other hand, this trend of weight reduction is well known to reduce vehicle stability in response to disturbances. Thus, automotive aerodynamic development is required not only to reduce aerodynamic drag, which contributes directly to lower fuel consumption, but also to develop technology for controlling unstable vehicle behavior caused by natural wind. In order to control the unstable vehicle motion changed by external contour modification, it is necessary to understand unsteady aerodynamic forces that fluctuating natural wind in real-world environments exerts on vehicles. In the past, some studies have reported the characteristics of unsteady aerodynamic forces induced by natural winds, comparing to steady aerodynamic forces obtained from conventional wind tunnel tests. Although there are few studies using full-scale vehicle, the characteristics of unsteady aerodynamic forces are not understood enough use for the vehicle development. In this study, a wind tunnel nozzle with oscillating plates and airfoils was newly developed for a full-scale wind tunnel. This device is called Natural Wind Generator (NWG) and can simulate natural wind with good repeatability. The authors attempted to clarify how unsteady aerodynamic forces induced by natural wind are different from steady aerodynamic forces. For experiments, a full-scale hatchback vehicle model was used. The unsteady aerodynamic forces acting on the model induced by the natural wind simulated using NWG were measured using a newly designed plate-type load cell. The comparisons between steady and unsteady aerodynamic forces show that the fluctuating aerodynamic forces induced by the natural wind have strong unsteady nature. In addition, the unsteady aerodynamic response characteristics evaluated by frequency response functions with respect to yaw angle fluctuations were changed to a great extent by modifying diffuser upsweep angles of the model. The evaluation method as mentioned in this study is effective to control unstable vehicle behavior caused by natural wind.

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## INTRODUCTION

Automotive manufacturers are proactively working to cut down on CO<sub>2</sub> emissions in recent years to reduce impacts to global warming. In order to accomplish that, it will be necessary to improve vehicle fuel efficiency. Each automotive manufacturer is promoting vehicle weight reduction as one of the fuel saving countermeasures. The weight reduction trend increases vehicle instability by increasing the ratio of aerodynamic forces to the inertia forces on vehicle. Thus, the aerodynamic development of passenger cars not only includes drag reduction, which contributes directly to lower fuel consumption, but also to develop technology for controlling unstable vehicle behavior caused by natural wind.

Drivers may feel discomfort based on various wind characteristics such as wind velocity fluctuation, wind direction fluctuation, turbulence intensity and turbulence length scale [1, 2, 3, 4, 5, 6, 7]. Table 1 shows the classification of unstable vehicle behavior caused by natural wind. The general term "crosswind stability" indicates the driving situation in which crosswind velocity and yaw angle are relatively high. Lateral and yawing vehicle motions become an issue

in this case. Some drivers point out unstable vehicle behavior in roll as well as lateral and yaw even in the case of relatively small disturbance [8]. This suggests the importance to understand how unsteady aerodynamic forces induced by these various properties of natural wind affect vehicle motion.

Table 1. The classification of unstable vehicle behavior caused by natural wind.

| Type of stability                    | Speed [km/h] | Crosswind [m/s] | Yaw angle of incoming flow [deg] | Focused vehicle behavior                             |
|--------------------------------------|--------------|-----------------|----------------------------------|------------------------------------------------------|
| Handling at high speed               | 100 – 200    | 0 - 3           | 0                                | Handling                                             |
| Stability under the hard crosswind   | 100 – 140    | 10 – 20         | 10 – 35                          | Yawing, Lateral Deviation                            |
| Stability under the slight crosswind | 140 – 200    | 2 – 7           | 2 – 10                           | Yaw, Lateral Deviation and Staggering in roll motion |

Conventional methods to assess crosswind stability for vehicle development include road tests that use several large fans along the side of a road and wind tunnel tests under constant yaw angles. The advantage of the former road tests is that the crosswind phenomena can be evaluated as coupled problems between aerodynamic forces and vehicle motion. However, the developer cannot quantitatively judge the superiority or inferiority of crosswind stability performance due to slight modifications of external contour, because data accuracy is insufficient and unable to be reproduced due to singular and unique conditions. In addition, the developer can evaluate the performance only when the crosswind is relatively large (yaw angles of 30 degrees and higher), which are rare in real environments. Regarding the latter developing method using static yaw angle tests in wind tunnels, evaluation is possible even in the case of small yaw angles. However, the differences between the steady aerodynamic forces generated by steady wind inputs and the unsteady aerodynamic forces induced by fluctuating natural wind become an issue. The reason is the difference between steady and unsteady aerodynamic forces or phenomena is not still completely understood.

Some experiments simulating natural winds in wind tunnels have been conducted in recent years, to find out the difference. Many of these experiments have adopted the method that oscillating devices such as airfoils are mounted at the nozzle exits of wind tunnels, so that fluctuating incoming flows to a vehicle can be generated [9, 10, 11, 12, 13, 14, 15, 16]. They have reported how much steady aerodynamic forces are amplified by fluctuating flows based on the concept of the aerodynamic admittance function originally introduced by Davenport [17]. Schrock et al. [13] and Stoll et al. [14] have conducted wind tunnel experiments using 20 – 25 % scale models, in which the resultant unsteady aerodynamic forces can be larger or smaller than the steady aerodynamic forces. Since the laws of similarity that apply between model-scale and full-vehicle-scale are not clear, the unsteady aerodynamic forces on full-scale vehicle cannot be predicted by results obtained from tests using scale models. Carlino et al. [15] reported the experimental results using SAE model of a simplified full-scale vehicle model. They have showed that unsteady aerodynamic forces differ from steady ones and that the characteristics of the unsteady aerodynamic forces are changed with shape modified. However, their study was limited to quite low frequencies of 1 Hz or less, where the response characteristics of unsteady aerodynamic forces to fluctuating natural wind cannot be clear. It also remains indistinct what would be the optimal external contour to control unstable vehicle behavior caused by natural wind.

In this study, unsteady aerodynamic forces on a full-scale hatchback vehicle model were measured at a relatively wide frequency range up to 5 Hz in Toyota's full-scale wind tunnel [18]. From the obtained results, the differences between the steady aerodynamic forces and the unsteady aerodynamic forces caused by fluctuating natural wind will be discussed. Also, it is illustrated how much the unsteady characteristics of aerodynamic forces can be controlled by modification of external contour.

## EXPERIMENTAL SETUP

### Natural Wind Generator (NWG)

The natural wind that occurs in on-road driving environment is classified by several characteristics such as wind velocity fluctuation, wind direction fluctuation, turbulence intensity and turbulence length scale. Wordley et al. [1, 2] and Lindener et al. [4] categorized natural wind of on-road environment in accordance with turbulence length scale and turbulence intensity. Sims-Williams [17] illustrated that the unsteadiness of flow around vehicle was closely related to turbulence length scale in incoming flow. Facilities in which developers can evaluate the unsteady aerodynamic characteristics, are very important not only from the viewpoint of the coupled problem with vehicle dynamics, but also for the aeroacoustics.

The authors have focused on the fluctuations of velocity and direction among several properties of natural wind. Figure 1 shows histograms of natural wind characteristics. The data was acquired on testing track on a windy day, using an X-type hot wire anemometer mounted on the hood of a vehicle. The authors developed a new evaluation device capable of reproducing these natural wind properties in Toyota's full-scale wind tunnel.

Figure 2 shows a picture and schematics of its functions. This device is called Natural Wind Generator (NWG). The detail of NWG is described by Terakado et al. [19]. The use of NWG requires removing the standard aerodynamic evaluation nozzle and replacing it with the NWG. The NWG nozzle has the same 7 m width, 4.5 m height and 15 m test article length as the standard nozzle [18] but differs from due to the addition of two vertical structures. The upper structure is called "damper plates", while the lower structure is called "airfoils". The heights of upper and lower structures are 1.25 m and 3.25 m, respectively. The damper plates on the upper side are composed of 20 plates with a rhomboid-shaped cross section. By operating two adjoining plates in opposite phase, the effective area of the nozzle outlet could be controlled, allowing for transient wind velocity fluctuation. The airfoils on the lower side are composed of 24 airfoils with a symmetric NACA0012 airfoil shape and it can provide fluctuations of yaw angle by changing their angles of attack to freestream. Both damper plates and airfoils are position-control enabled to as high as 5 Hz by water-cooled servo motors. Table 2 shows this device's reproducibility performance. NWG can simulate velocity fluctuations of 28 % with respect to freestream velocity of 120 km/h, and yaw angle fluctuations up to 15 degrees.

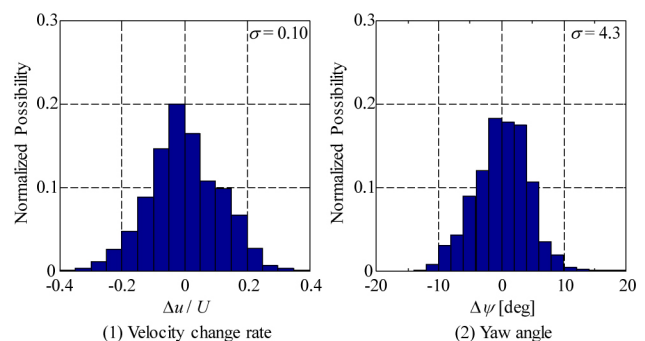


Figure 1. Histograms of natural wind characteristics obtained by on-road test at 120 km/h (Left: velocity fluctuation, Right: yaw angle fluctuation).

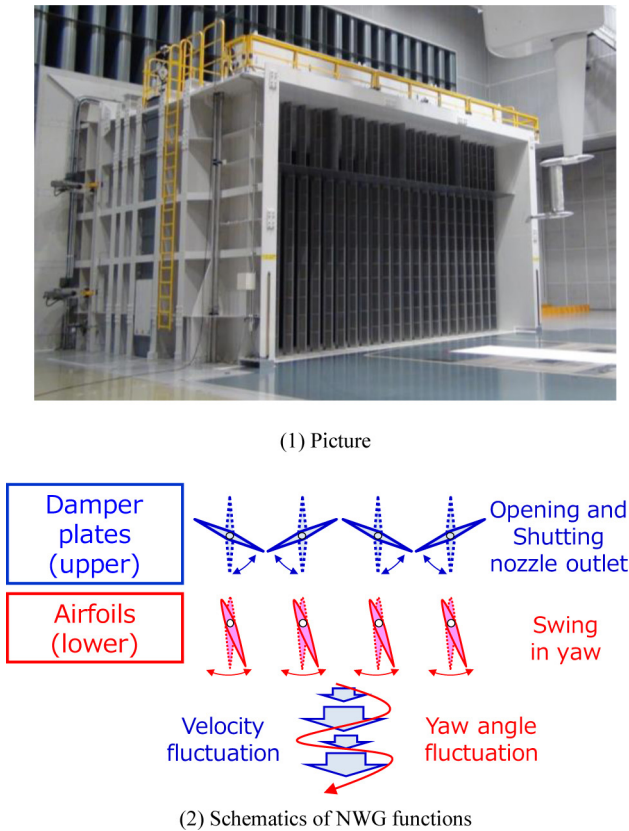


Figure 2. A picture and schematics of Natural Wind Generator (NWG).

Table 2. Performance Specification of NWG.

|                                 | Functions                                | Maximum of Reproducible Frequency (Hz) | Maximum Performance         |
|---------------------------------|------------------------------------------|----------------------------------------|-----------------------------|
| Damper plates (upper structure) | Generate freestream velocity fluctuation | 5                                      | 28 % of freestream velocity |
| Airfoils (lower structure)      | Generate yaw angle fluctuation           |                                        | +/- 15 [deg]                |

The natural wind characteristics shown in Figure 1 were reproduced using NWG. Figure 3 shows time variations of velocity and yaw angle fluctuations. Figure 4 shows power spectra of time variations shown in Figure 3. These data was measured at the vehicle mounting position and 1.5 m height by X-type hot wire anemometer. The turbulence intensity of natural wind was 10 %, while that of reproduced wind was 8 %. The turbulence length scale calculated by auto-correlation method was 1.8 m. These properties of 8 % turbulence intensity and 1.8 m turbulence length scale is comparable to the condition with road side obstacle mentioned by Wordley [1] or the strong traffic condition stated by Lindener et al. [4]. The yaw angle deviation of natural wind was 4.3 deg, while that of reproduced wind was 3.7 deg. It can be seen that NWG can roughly reproduce the properties of natural wind.

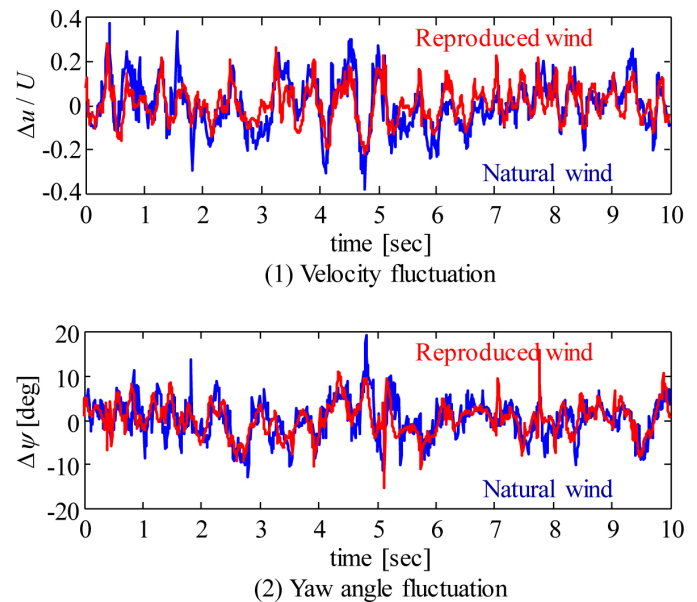


Figure 3. A comparison of wind characteristics between natural wind obtained from on-road test and reproduced wind by NWG.

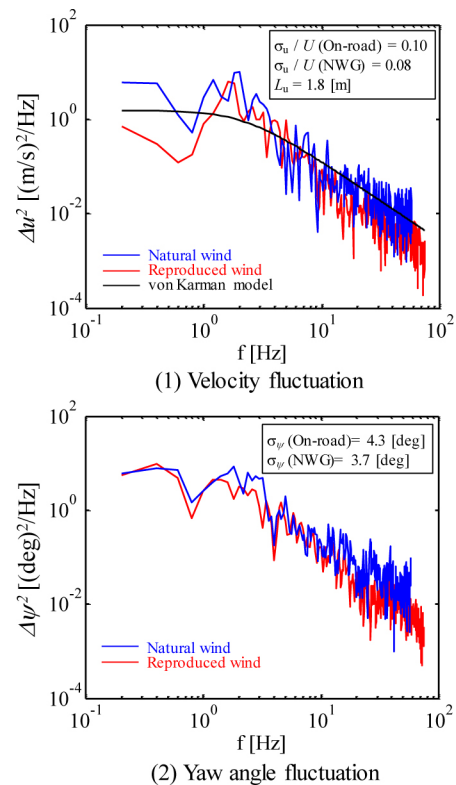


Figure 4. Power spectra of wind characteristics reproduced by NWG.

Figure 5 shows dimensionless time-averaged velocity profiles for the case of reproduced wind shown in Figure 3. Figure 6 shows the profiles of yaw angle amplitude. These profiles were also measured at the vehicle mounting position by moving X-type hot wire anemometer vertically and horizontally. Although the horizontal velocity profile is uniform, the vertical velocity profile is uneven. This non-uniformity is caused by NWG structure that the damper plates are located at the upper portion of nozzle. The horizontal region below 2 m height of ordinary vehicle height is almost uniform.

On the other hand, yaw angle profiles show to be almost uniform over the plenum of test section. For these result, the authors defined velocity and yaw angle fluctuations at model mounting position and 1.5 m height as the representative properties of NWG. These results show a newly developed NWG has a potential of reproducing various natural winds.

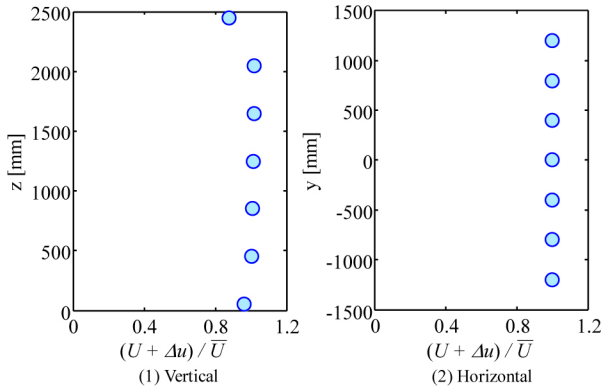


Figure 5. Dimensionless time-averaged velocity profiles for the case of reproduced wind by NWG.

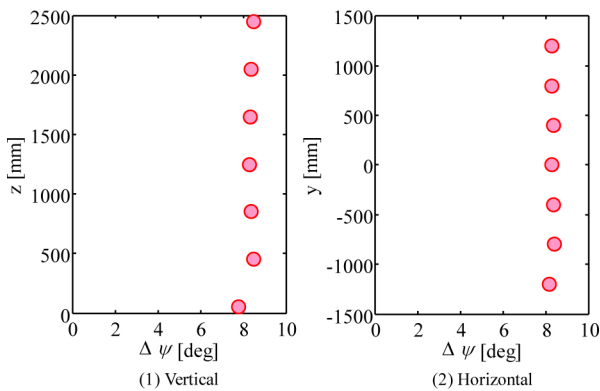


Figure 6. Profiles of yaw angle amplitude for the case of reproduced wind by NWG.

## Experimental Model

Figure 7 shows schematics of experimental model used in this study. A full-scale hatchback model simplified from a real vehicle was used. The model's dimensions are length  $L = 4.3$  m, width  $W = 1.8$  m, height  $H = 1.5$  m, wheelbase  $WB = 2.6$  m, and frontal projected area of this model  $A = 2.131$  m<sup>2</sup>. In order to simplify the phenomena being observed, the surface of this model is smoothed, and ventilation systems are not simulated. Two external contours, which are closely related to aerodynamic drag reduction, were compared. "Shape A" has a 0 degree diffuser upsweep angle of the rear floor. "Shape B" has a diffuser angle of 8 degrees. In order to precisely measure temporal fluctuations in aerodynamic forces, it is essential to have highly responsive measurement system including an experimental model. Thus, the structure of this model was analyzed using FEM analysis before manufacturing the model. The results concluded that the model should have been made of CFRP and aluminum honeycomb. The model had the characteristics of light weight (150 kg) and high rigidity (primary resonance mode: 60 Hz).

## Unsteady Aerodynamic Force Measurement System

The load cell is also required to be with good accuracy and high responsiveness. The five-belt system which is usually equipped in Toyota's full-scale wind tunnel is too slow of a response time for this study. Therefore, four sets of the thin plate-type load cell were newly developed as shown in Figure 8. Each load cell is very lightweight of 11 kg, so that it can be easily carried. The performance specification of load cell is summarized in Table 3. The load cell can measure loads with high precision, and its characteristic frequency is sufficiently high.

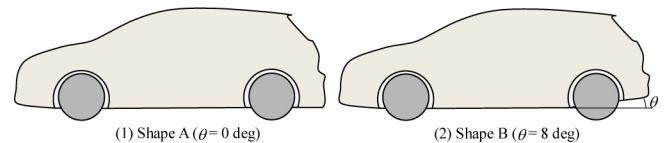


Figure 7. Schematics of experimental models.

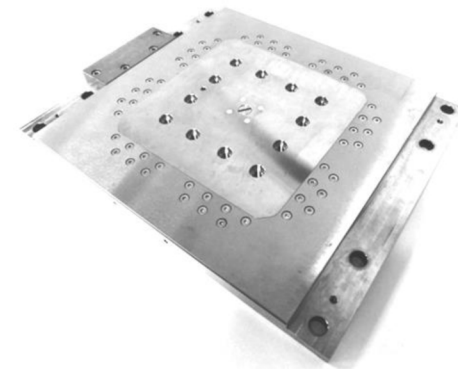


Figure 8. Picture of the newly developed plate-type load cell.

Table 3. Performance specification of the newly developed load cell.

| Axis  | Rated Force & Moment | Measurement Accuracy | Resonant Frequency |
|-------|----------------------|----------------------|--------------------|
| $F_x$ | +/- 2000 [N]         | +/- 0.8 [N]          | 1 kHz              |
| $F_y$ | +/- 2000 [N]         | +/- 0.8 [N]          | 1 kHz              |
| $F_z$ | - 8000 to 0 [N]      | +/- 3.6 [N]          | 600 Hz             |
| $M_x$ | +/- 400 [Nm]         | 0.3 [Nm]             | 1 kHz              |
| $M_y$ | +/- 400 [Nm]         | 0.3 [Nm]             | 1 kHz              |
| $M_z$ | +/- 400 [Nm]         | 0.2 [Nm]             | 2 kHz              |

## Measurement Setup

All tests were conducted in Toyota's full-scale wind tunnel with NWG installed. Figure 9 provides a picture of the experimental setup. The model was installed in the center of the plenum with the plate-type load cells, which were located under all four of stings to measure aerodynamic forces. Aerodynamic forces acting on the model were calculated by converting the six component force measured by each load cell into the combined force at the wheelbase center (origin). Three components of side force  $F_y$ , roll moment  $M_x$  and yaw moment  $M_z$  are shown in this paper. The tires were isolated from the measurement system, and put on the ground. This means that the resultant aerodynamic forces do not include the forces on four tires. Also, the ground simulation system including the boundary layer suction and the tire rotating systems was not provided. The incoming flow fluctuations in velocity and yaw angle generated by