

Development of Full-Scale Wind Tunnel for Enhancement of Vehicle Aerodynamic and Aero-Acoustic Performance

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ABSTRACT

A new wind tunnel was developed and adopted by Toyota Motor Corporation in March 2013. This wind tunnel is equipped with a 5-belt rolling road system with a platform balance that enables the flow simulation under the floor and around the tires in on-road conditions. It also minimizes the characteristic pulsation that occurs in wind tunnels to enable the evaluation of unsteady aerodynamic performance aspects. This paper describes the technology developed for this new wind tunnel and its performance verification results. In addition, after verifying the stand-alone performance of the wind tunnel, a vehicle was placed in the tunnel to verify the utility of the wind tunnel performance. Tests simulated flow fields around the vehicle in on-road conditions and confirmed that the wind tunnel is capable of evaluating unsteady flows.

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1. INTRODUCTION

The constant improvement of vehicle aerodynamic performance plays a key role in the enhancement of performance aspects such as fuel economy, comfort, and kinetic performance. For this reason, many automakers have developed wind tunnels to simulate on-road conditions more accurately [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11].

Wind tunnels have been developed with either a 1- or 5-belt rolling road system. In general, most wind tunnels have a nozzle size of approximately 25 m² and a maximum velocity between 200km/h and 300 km/h. Low-noise wind tunnels for evaluating wind noise generally have a background noise level from 60 to 70 dB at 160km/h. Some wind tunnels have been developed with the capability of evaluating both aerodynamic characteristics and wind noise. Almost recent developed wind tunnels have adopted technologies to reduce pulsation. [1][2][7][12][13][14]. As a whole, technological trends for wind tunnels have focused on the evaluation of on-road flow fields, including unsteady flows.

Toyota Motor Corporation is also working to drastically improve aerodynamic performance with the following technology development.

- Coefficient of drag (CD) reduction by improving flows under the floor and around the tires, cooling airflow in the engine compartment, and by focusing on unsteady flow phenomena.
- Dynamic performance enhancement through aerodynamic characteristics considering fluctuation in flows by controlling unsteady flows.
- Wind noise reduction adopting countermeasures for noise sources at the modeling stage.
- Enhancement of flow-related aerodynamic performance (such as water and dirt accumulation) by understanding flow fields around the vehicle more accurately and efficiently.

To achieve these performance improvement, research is being carried out to understand the principles of on-road flow fields, including the characteristics of unsteady flows that have yet to be fully identified. As part of these efforts, a full-scale wind tunnel has been developed with the following concept.

- Develop a wind tunnel that is capable of simulating on-road flows to enable the measurement of aerodynamic characteristics with high accuracy and repeatability.
- Develop a wind tunnel that suppresses pulsation and that can evaluate unsteady flows around the vehicle.
- Develop a wind tunnel capable of creating flow fields for simulating on-road environments and that has low levels of noise to enable the evaluation of noise generated by external shapes and interior noise.
- Develop a wind tunnel with an efficient measurement system capable of fully understanding flow fields around the vehicle to enable airflow design.
- Develop a wind tunnel to enable close cooperation within the company between styling, design and other fields, with the aim of promoting smooth development of aerodynamic characteristics.

This paper describes the development of this new wind tunnel, which was completed in March 2013, and its performance verification results.

2. TARGET WIND TUNNEL PERFORMANCE

The following critical performance targets were set in the development of this wind tunnel. The concrete targets show in [Table 1](#). Definition of the coordination in wind tunnel shows in [Fig.1](#).

1. Substantial reduction in pulsation: The targeted performance was achieved by adopting a special flow installing system ([Fig. 2](#)), pulsation reducing opening, and flow installing system exit ([Fig. 3](#)), as well as by applying fabric materials and an acoustic transmission structure to the collector ([Fig. 4](#)).
2. Flat static pressure distribution in the axial direction and within each cross-section: This was achieved by optimizing the combinations of three parameters (i.e., the nozzle outlet angle, rate of suction from the flow installing system, and collector/nozzle area ratio).
3. Wide and uniform velocity distribution: This was achieved by adopting large area nozzle (7m times 4.5m) and three rectifying mesh screens and one honeycomb.
4. A wind tunnel capable of evaluations of both aerodynamic characteristics and wind noise: This was achieved by adopting thorough sound-absorption structure, reduction of sound pressure level from sound source and flow installing system [20].

This research particularly focused on target 1, the reduction of pulsation. As a result, the developed wind tunnel is capable of accurately evaluating unsteady aerodynamic performance. Conventional technological development for reducing the CD of mass-production vehicles, enhancing dynamic performance through aerodynamic characteristics has focused on steady flow evaluations (i.e., evaluations using average values) and localized optimization of external shapes. However, this approach is reaching its limits and a breakthrough in the development of aerodynamic performance is required. To resolve this issue, this research focused on unsteady flow phenomena to develop a new method of controlling flows. The use of this pulsation-minimizing wind tunnel in vehicle development is capable of speeding up studies based on detailed physical analysis of flow, thereby facilitating the incorporation to production vehicles with innovative technologies to reduce CD and technologies to enhance dynamic performance through aerodynamic characteristics.

Table 1. Target performance.

	Evaluation value	Target	Measured Region
Reduction in pulsation	Static Pressure fluctuation Cp,max-Cp,min in 140 km/h (peak-to-peak value of pressure. Evaluation details in Section 4.2.1)	<0.093 in 0.25 Hz to 10 Hz <0.015 in 10 Hz to 30 Hz	X= -3 m to 3 m Y= -2 m to 2 m Z= 0.15 m to 3 m
	Static Pressure fluctuation sweep Cp,rms in 80 to 250 km/h	<0.0094 in 0.25 Hz to 30 Hz	X=0 m Y=2 m Z=1.5 m
Flat static pressure distribution	Static pressure distribution Cp at X=-2.7 m to Cp at X=3 at 140 km/h	<0.002	X= -2.7 m to 3 m Y= -2.5 m to 2.5 m Z= 0.15 m to 3.5 m
	Static pressure gradient dCp/dx at 140 km/h	<0.002 /m	
Uniform velocity distribution	Velocity distribution uniformity (Umax - Umin) / Uave	<0.5 %	X=0 m Y= -2.8 m to 2.8 m Z= 0.1 m to 3.5 m
Background noise	Over all value (Spectrum target is shown in Fig. 19 with the confirmation result)	<44.5 dB(A) at 80 km/h <50.5 dB(A) at 100 km/h <62.5 dB(A) at 150 km/h <71.4 dB(A) at 200 km/h	X=0 m Y=5 m Z=1.25 m

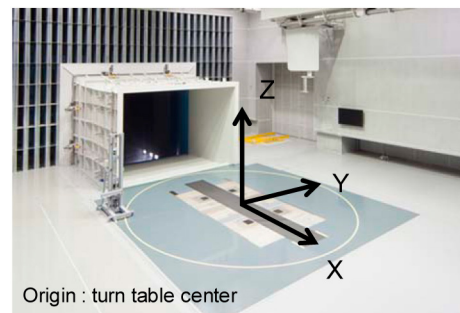


Figure 1. Definition of coordination.

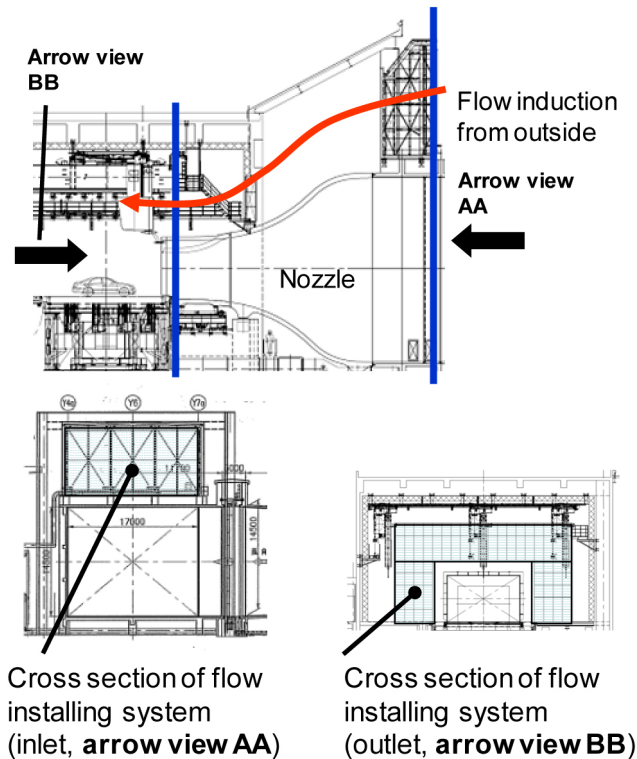


Figure 2. Flow installing system.

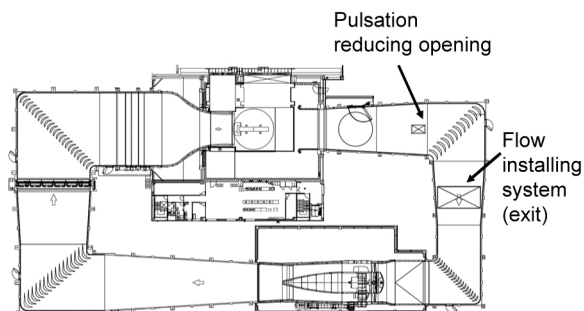


Figure 3. Pulsation reducing opening.

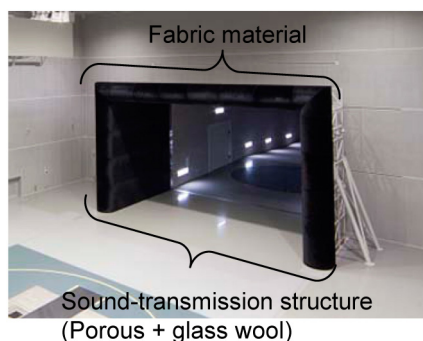


Figure 4. Collector.

3. WIND TUNNEL TECHNOLOGIES TO ACHIEVE PERFORMANCE TARGETS

3.1. Development of Wind Tunnel Technologies to Reduce Pulsation

First, this section describes the technologies developed to achieve Target 1: a substantial reduction in pulsation.

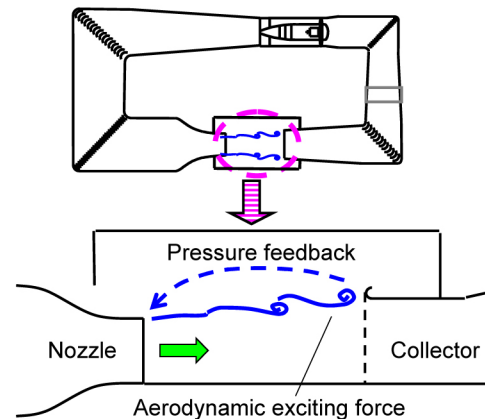


Figure 5. Mechanism of edge-tone mode in measurement room.

3.1.1. Pulsation Generation Mechanism

In a wind tunnel for evaluating aero-acoustic sound such as wind noise, leak noise, etc., the test section is generally open to enable the simulation of free sound fields and to measure various acoustic elements. However, an open jet test section is susceptible to the generation of aero-acoustic fluctuations as shown in Fig.5. Fig. 5 shows the edge-tone mode generation mechanism. Furthermore, the characteristics of the closed-loop wind tunnel circuit causes low frequency pressure fluctuation called "tunnel mode". The prominent pulsation results from the resonance of both modes of "edge-tone mode" and "tunnel mode". Previous research has described the causes of pulsation as follows [1][2][7][12][13][14][15][16].

1. Pressure feedback between the nozzle and collector (self-excited oscillation): The jet flow discharged from the nozzle has strong vortex structure. Fluctuations in velocity and pressure are generated by drastic vortex accelerations and decelerations close to the downstream collector. These pressure fluctuations excite the nozzle vortex flows and generate a feedback loop, resulting in self-excited pressure fluctuations (edge-tone mode)
2. Acoustic characteristics of overall closed-loop wind tunnel circuit: In a full-scale wind tunnel, the wind tunnel circuit is long and has a low acoustic eigenvalue (tunnel mode).

Pulsation is generated by resonance created through the interaction of the two above mentioned modes.

3.1.2. Examination of Pulsation Reducing Countermeasures

Various successful countermeasures have already been adopted to reduce pulsation [1][2][7][12][13][14][15][16], however, further reductions are needed to enable the highly accurate evaluation of unsteady flow around the vehicle. This research examined the introduction of the following new technologies and systems [16][20].

1. Suppression of pressure feedback between nozzle and collector: (i) adoption of flow installing system (Fig. 2) and (ii) collector technology (acoustic transmission structure and fabric materials) (Fig. 4)
2. Reduction of acoustic resonance of overall closed-loop wind tunnel circuit: Pulsation reducing opening and exit of the flow installing system (Fig. 3).

The flow installing system reduces the pressure acting on the collector by smoothing the flow to the collector. Applying fabric material and an acoustic transmission structure to the collector surface also reduces the pressure acting on the collector and lowers pressure reflection. In addition, openings were provided at the location where the pressure wave reaches a peak to reduce the acoustic resonance of the overall wind tunnel circuit. There are two openings. One is flow installing system exit. The other opening is called the pulsation reducing opening.

The entrainment flow from the flow installing system to the test section is generated by the main flow of the wind tunnel. The entrainment flow rate can be calculated by the empirical equation (1) on flow entrainment [20]. If the entrainment flow rate is 0.3, the entrainment flow from the inlet in the test section is about 4 m/s at 140km/h.

$$\beta = \frac{Q_b}{Q_{th}}, Q_{th} = \left\{ 0.14 \frac{L}{D_n} + 0.018 \left(\frac{L}{D_n} \right)^2 \right\} Q_n \quad (1)$$

where, β is the entrainment flow rate, Q_b is the entrainment flow volume, Q_{th} is the theoretical entrainment flow volume, L is the length of the test section (from nozzle exit to the collector), D_n is the hydraulic diameter of the nozzle.

3.1.3. Verification in 1/10th Scale Wind Tunnel

These pulsation reducing measures were verified in a 1/10th scale wind tunnel. Fig. 6 shows the comparative results between the 1/10th scale wind tunnel and two other wind tunnels [2][21]. The comparison data of other tunnels is transcription by grid sheet. It indicates that static pressure fluctuations have been suppressed at all velocities. This confirmed the effectiveness of the developed pulsation reducing technologies.

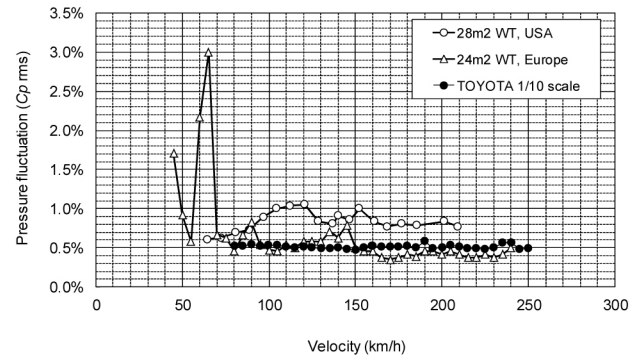


Figure 6. Pressure fluctuation at turntable center (Z=0.15 m) in 1/10th scale wind tunnel compared with other wind tunnels.

3.2. Development of Technologies for Flat Static Pressure Distribution

This section describes the technologies developed to achieve Target 2: flat static pressure distribution in the axial direction and within each cross-section.

The main dimensions of the measurement room were determined using computational fluid dynamics (CFD) and the 1/10th scale wind tunnel. To achieve a uniform upstream static pressure, the specifications of the nozzle outlet were optimized. The rate of flow induction from the flow installing system was also optimized to control reductions in the surrounding static pressure due to circulating flow within the measurement room. Then, to achieve a uniform downstream static pressure, the area of the collector and nozzle outlet were set to the optimal ratio. Combinations of these three parameters (i.e., the nozzle outlet angle, rate of suction from the flow installing system, and collector/nozzle area ratio) were examined to determine the best specifications to achieve an overall flat static pressure.

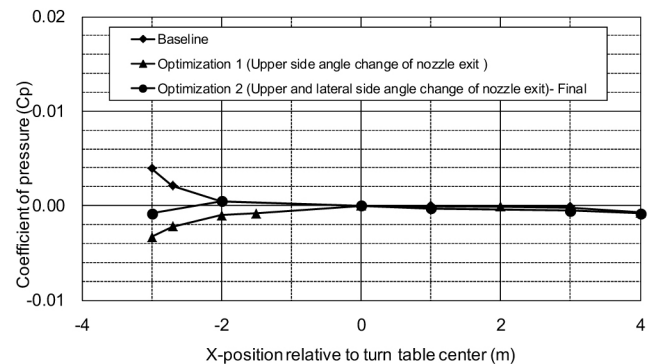


Figure 7. Static pressure distribution in 1/10th scale wind tunnel. The effect of nozzle exit angle.

Fig. 7 shows the representative example of measurement results on the nozzle exit angle optimization for static pressure distribution as verified in the 1/10th scale wind tunnel. The static pressure distribution is the X-direction distribution of the average static pressure coefficient in a cross-section measuring from -2.5 m to 2.5 m in the Y-axis and from 0 m to 3.5 m in the Z-axis on the actual wind tunnel scale. The

difference in the static pressure coefficient at the front ($X=-2.7$ m) and rear ($X=3$ m) edges was 0.0006 and the maximum static pressure gradient was 0.001/m. Actually, many cases of nozzle outlet angle, rate of suction from the flow installing system, and collector/nozzle area ratio for optimization was conducted. This confirmed the effectiveness of the optimized those three parameters.

3.3. Technology Configuration for Wide and Uniform Airflow Velocity Distribution

This section describes the technologies developed to achieve Target 3: Wide and uniform velocity distribution.

The nozzle geometry was optimized to achieve a low turbulence intensity, as well as the target airflow velocity distribution and static pressure distribution. The nozzle length was set to 17 m with a Rouse-Hassan curve [17] and a contraction ratio of 8. Three rectifying mesh screens and one honeycomb were installed upstream of the nozzle to create a uniform velocity.

Fig. 8 shows the measurement results for velocity distribution in the 1/10th scale wind tunnel. In a range measuring from 0 m to 2.8 m in the Y-axis and from 0.1 m to 3.5 m in the Z-axis on the actual wind tunnel scale, the maximum deviation in the velocity distribution (i.e., maximum velocity - minimum velocity) was 0.15% with respect to the cross-sectional average. This confirmed the appropriateness of the nozzle geometrical design and rectifying mesh screen installation.

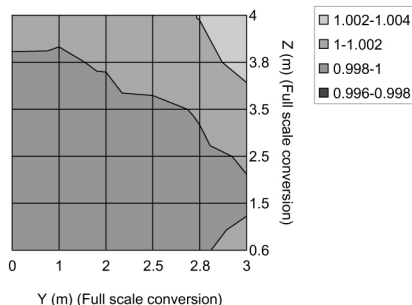


Figure 8. Velocity distribution in 1/10th scale wind tunnel.

3.4. Development of Wind Tunnel to Evaluate Aerodynamic Characteristics and Wind Noise

This section describes the technologies developed to achieve Target 4: a wind tunnel capable of evaluations of both aerodynamic characteristics and wind noise.

The sound sources inside a wind tunnel circuit are as follows: the main fan, nozzle, collector, boundary layer intake devices, floor surface, and sounds entering from outside the wind tunnel circuit. Fig. 9 shows the countermeasures for each sound source. To reduce propagation of sound from the main fan, sound-absorption ducts were provided at the fan outlet. In

addition, as shown in Fig. 9, most of the inner walls of the wind tunnel circuit are constructed from a sound-absorption concrete called Porecell.

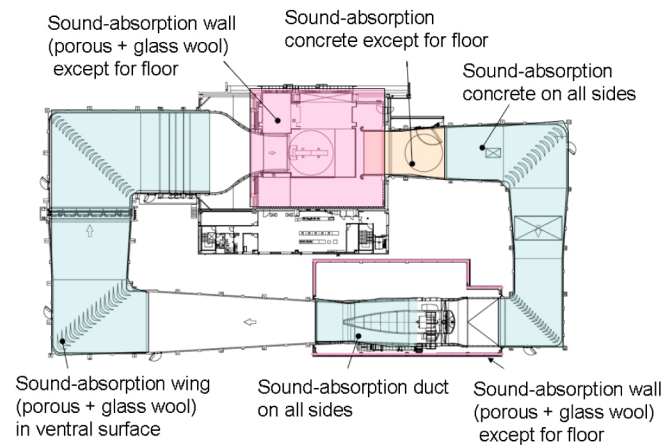


Figure 9. Background noise reduction.

Fig. 10 shows the Porecell on the wall. The "Porecell" is lightweight-cement-rigid-porous acoustic absorption material that consists primarily of cement and silica with many small bubble of the diameter 0.1mm to 1.0mm. The degree of sound absorption of the Porecell due to reverberation room method is 0.6 at 125 Hz and almost 1 over 250 Hz [22]. Turning vanes constructed from porous metal plates and glass wool were also added to form sound-absorption wing structures. Based on the results of component tests, these turning vanes form a sound-absorption wing structure, excluding only 10% of the surface area at the front and rear edges. However, no special sound-absorption measures were applied to the nozzle to achieve the required aerodynamic performance requirements. The collector is impacted by strong eddy flows affected by the shear layer generated by the nozzle outlet. These vortex flows cause fluctuations in velocity and pressure, and are a source of noise. Therefore, fabric materials were applied to the collector nozzle to form an acoustic transmission structure inside the collector.

Fig. 11 shows the illustration of the acoustic transmission structure and the fabric material. The structure consists of porous metal plates, glass wool and fabric material. The property of the fabric material is referred to [23].

The first boundary layer intake device was designed with oval scoop geometry to suppress fluctuations in pressure and velocity caused by separation of the flow at the edge. Level differences and gaps were minimized to reduce sounds generated from the floor. Since most sounds entering from outside the wind tunnel circuit emanate from the inlet of the flow installing system, a silencer comprising porous plates and sound-absorption materials was provided in the intake circuit to suppress sounds entering from outside. In addition, operation sounds from the motor etc. were minimized by covering sound sources with an enclosure box.