

Development of a New Pressure Measurement Technique and PIV to Validate CFD for the Aerodynamics of Full-scale Vehicles

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ABSTRACT

In the early stages of aerodynamic development of commercial vehicles, the aerodynamic concept is balanced with the design concept using CFD. Since this development determines the aerodynamic potential of the vehicle, CFD with high accuracy is needed. To improve its accuracy, spatial resolution of CFD should be based on flow phenomenon. For this purpose, to compare aerodynamic force, pressure profile and velocity vector map derived from CFD with experimental data is important, but there are some difficulties to obtain pressure profile and velocity vector map for actual vehicles.

At the point of pressure measurement for vehicles, installation of pressure taps to the surface of vehicle, i.e., fuel tank and battery, is a problem. A new measurement method developed in this study enables measurement of surface pressure of any desired points. Also, the flexibility of its shape and measuring point makes the installation a lot easier than the conventional pressure measurement method.

In the case of velocity vector measurement, there are two main problems. The first is the measurable domain by PIV is too small for a real vehicle. To solve this, simultaneous multi-camera stereoscopic-PIV that can measure enough size for the wake flow is developed. The second problem is how to validate the flow around the underfloor. For the measurement of such flow, a small probe-type PIV system consisting of a small camera, a laser fiber and a large particle seeder has been developed.

By using these validation techniques, the results of RANS and LES are accessed and discrepancies between experimental results are clarified in this paper.

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INTRODUCTION

In the early stages of aerodynamic development of commercial vehicles, the aerodynamic concept is balanced with the design concept. Also at this stage, aerodynamic potential (e.g. drag or drivability caused by aerodynamics) of vehicles is determined. Therefore aerodynamic performance of several vehicle styling is tested with large model deformation. At this early stage, the development with CFD (Computational Fluid Dynamics) is more efficient than wind-tunnel testing, because the time required to change styling is shorter than in wind-tunnel testing. In addition to this benefit, aerodynamicists are able to suggest visually an aerodynamic concept to exterior stylists based on flow phenomenon [1] using CFD. When the deformation of the model surface decreases, aerodynamic optimization work is efficiently conducted in the wind tunnel.

To develop a good vehicle package and styling and to provide insight to the optimization work, the accuracy of CFD is important. To improve the accuracy of CFD, RANS (Raynolds Averaged Navier-Stokes equations), URANS (Unsteady Raynolds Averaged Navier-Stokes equations) [2], LES (Larger Eddy Simulation) [3] and hybrid

Methods [4] are adapted to vehicle shapes. Among these methods, LES is one of the most theoretical. Turbulent models of LES are based on the physics of fine-scale eddies that have universal characteristics, so accuracy strongly depends on spatial and temporal resolution. Matsumoto reported that the Smagorinsky model well correlates with filtered DNS (Direct Numerical Simulation) in the case of Δ (Δ :filter width) being larger than 30η (η : Kolmogorov scale)[5]. On the other hand, Δ should be set sufficiently small to accurately predict the energy transfer from mean flow to wake region. Therefore, if spatial distribution of η around the vehicle is experimentally measured, then the optimal size of Δ is decided based on physics.

Several hypotheses to calculate η by using experimental methods are reported[6][7], so some measurements techniques, like LDV (Laser Doppler Velocimetry), PIV (Particle Image Velocimetry)/PTV (Particle Tracking Velocimetry) or hotwire are adapted to measure η to validate SGS (Subgrid scale) model [8] or the results of DNS. Among these techniques, PIV has the potential to efficiently measure the spatial distribution of η around the vehicle because PIV can measure the distribution of turbulent structures in a plane or volume.

In addition to this benefit, grid-type vector definition point obtained by PIV is suited for the calculation of η , because the spatial derivative of velocity vector is needed to calculate η . However, PIV has two of main issues to measure the flow around an actual vehicle. The first is the measurable domain is too small to measure its wake, and the second is optical access for the flow around the under-floor.

In addition to those above noted, much time is needed to set up the PIV system and to change the measurement plane. Therefore, the most important point of PIV measurement is to decide measurement planes for the effective experiment and validation work before PIV testing. To decide measurement planes, conducting surface pressure measurement before PIV measurement is one of the most efficient methods, but the common method of making pressure taps on the surface of the actual vehicle restricts the measurable area and costs about 100\$/tap, so conducting a surface pressure measurement around the actual vehicle also requires great resource.

In this study, a new sophisticated surface pressure measurement technique and two types of PIV are developed to obtain validation data of CFD.

DEVELOPMENT OF A NEW PRESSURE MEASUREMENT TECHNIQUE

It is difficult to apply conventional pressure taps method to measure surface pressure of some parts that will lose their function by making pressure taps, e.g. the fuel tank and battery. It is also difficult to apply this method to structural parts, because of the accessibility to the rear of these parts. To solve this issue, pressure discs are often used for the surface pressure. Nouzawa uses pressure discs to measure the surface pressure of the trunk deck [9]. Even if it is easy to attach pressure discs on the surface, the diameter of the pressure disks (25mm to 50mm) restricts attachment to rounded surfaces.

To solve this issue, flexible pressure measurement tubes, as shown in Fig.1, are used in the development of airplanes. The typical thickness of these tubes is about 2-3mm, so measured pressure value is accelerated and is not negligibly small for thin aero parts, like strakes or wings. A non-intrusive pressure measurement method, PSP (Pressure Sensitive Paint), has the ability to measure pressure with high accuracy at high speed, but the sensitivity of PSP is not sufficient for flow slower than 30m/s. Therefore, to validate wake flow using PSP is challenging. In addition to this issue, optical access is a more important issue for the flow around the vehicle, because flow around under-floor should be validated with CFD and experimentation.

Figure 1 shows schematics of "Strip Tube." Strip Tube consists of 10 pressure tubes and the width and height of the Strip Tube are 8.0mm and 1.0mm, respectively. There is no length limitation. One end of the Strip Tube is sealed so as not to leak pressure and the other end leads to a pressure sensor. Pressure holes can be made at any desired place. The Strip Tube is made of Hytrel (DU PONT-TORAY CO., LTD.) and the limit of operating temperature is about 120°C. This temperature limit makes it possible to measure most of the surface of the vehicle except very hot places, such as exhaust pipe, catalyzer,

etc. The minimum diameter of the deflection curvature of Strip Tube is about 10mm. The cost of Strip Tube is \$10/m, so it is much cheaper than the conventional pressure tap method.

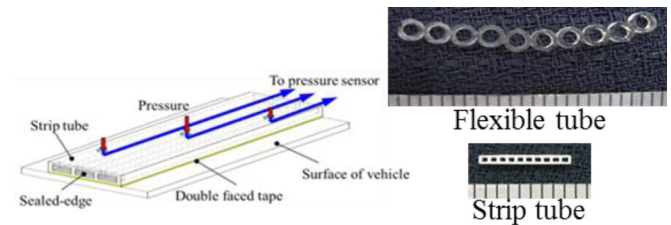


Figure 1. Schematics and "Strip Tube" and cross-section of conventional flexible pressure tube and "Strip Tube."

Measurement error caused by the thickness of the Strip Tube was examined by attaching the Strip Tube on a two-dimensional NACA0012 wing section (chord length of 600mm) as shown in Fig. 2. The Strip Tube is aligned parallel to mean flow and α (attack angle) is set to 10degrees. Figure 3 shows a comparison of C_p value measured using the Strip Tube and pressure taps on the wing. Maximum and mean deviation of C_p between the two methods are -0.02 and -0.007, respectively.

Measurement error where the pressure gradient is large is strongly affected by the accuracy of the precisely installed position of the Strip Tube on a surface. If installation error is assumed as 1mm, then installation error becomes the main cause of measurement error where the pressure gradient is larger than 0.02 C_p /mm. In the case of this NACA0012 wing at $\alpha = 10$ degree, this region ranges from 0 to 5mm.



Figure 2. Strip Tube on NACA0012 wing.

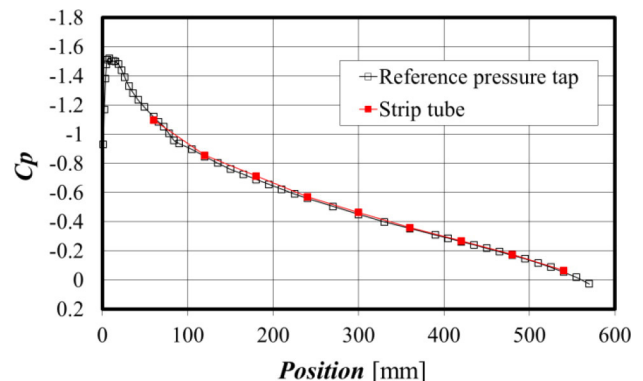


Figure 3. Comparison of C_p value measured by Strip Tube and pressure taps at $U=83.3$ m/s and $\alpha=10$ degree.

The investigation of measurement error when the Strip Tube was aligned at some angles was conducted as shown in Fig. 4. Pressure taps on the wing section were aligned parallel to the mean flow, the same as above. Figure 5 shows the relationship between measurement error dC_p and θ (slant angle). The assessed point shown in Fig. 5 locates at 60mm (10% chord length). dC_p is the difference between C_p measured by the Strip Tube and pressure tap on the wing section. The pressure measurement point on the Strip Tube compared with the pressure tap on wing shown in Fig. 5 is the most outer channel of the Strip Tube, because its error becomes greatest at this point. Measurement error increases with the increment of alignment angle. This means that the Strip Tube should basically be set parallel to the flow and the typical measurement error of the Strip Tube ranges from -0.01 to -0.02 in C_p . Due to this limitation, some additional care, for example making a slant beside a Strip Tube or to examine the flow direction, are needed to mount the Strip Tube on the A-pillar.

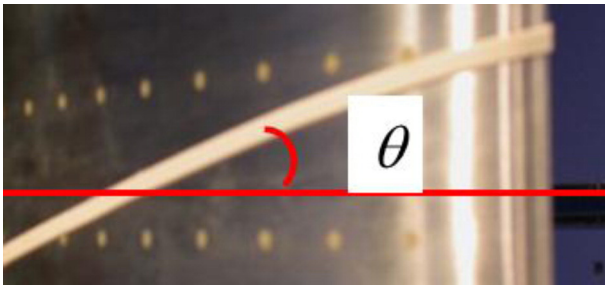


Figure 4. Strip Tube on NACA0012 wing with slant angle.

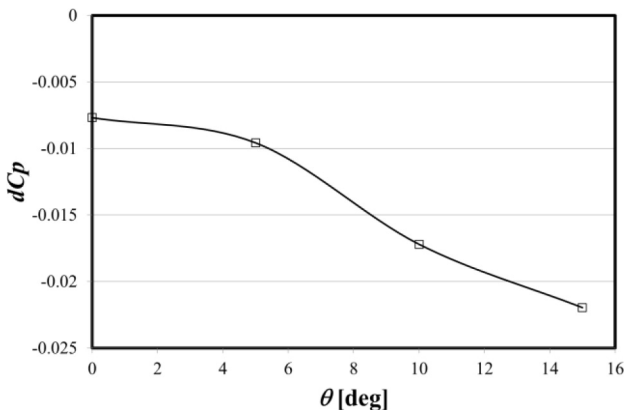


Figure 5. Relationship between measurement error and slant angle. (α is set to 7 degree, $U=70\text{m/s}$)

DEVELOPMENT OF NEW PIV TECHNIQUES

To enlarge the measurement domain, laser energy density, spatial resolution, brightness of camera, reflection from objects and diameter of tracer particles are important parameters for PIV measurement. Even using an 11M-pixels camera and 180mJ laser with diameter of $1\mu\text{m}$ tracer particles, measurable domain is suited for 25%-scale vehicle model [10]. The brightness of the particle image is mainly proportional to the square of particle diameter and restricts measurable domain. In this study, a new PIV seeder is developed using a pneumatic seeding nozzle (AKI nozzle D, H. IKEUCHI & Co., LTD.). Hoshino reports that measurable domain increases using pneumatic seeding nozzle compared with when Laskin nozzle (PIV part40, SEIKA Digital Image Corporation) is used [11]. In this study,

a pneumatic nozzle is covered by a cylindrical-type fairing to reduce large particles that do not follow the flow and contaminate the wind-tunnel and models as shown in Fig. 6.

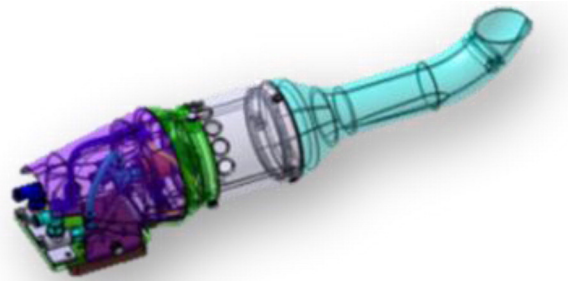


Figure 6. A new PIV seeder with pneumatic nozzle.

Figure 7 shows a probability density function of particle diameter generated by each seeding nozzle. DEHS is used as seeding oil for each nozzle. A Laskin nozzle is widely used for PIV, and the mean diameter of the Laskin nozzle is $1\mu\text{m}$. On the other hand, the red line shows the probability function of a new seeding nozzle. Tracer particles that are smaller than $4\mu\text{m}$ tend not to attach to the walls of the wind-tunnel or vehicle in normal test conditions of automobiles. It is clear that larger particles are eliminated by a cylindrical-type fairing. The mean diameter of this pneumatic nozzle with fairing is $2\mu\text{m}$. The relaxation time that is defined by equation (1) is $11\mu\text{s}$. This means that the maximum error of vector definition position, for example under a condition of 50m/s , is about 0.55mm . This error is negligibly small for a meter-scale measurement, because typical spatial resolution of this condition is about $10\text{-}20\text{mm}$.

$$t_s = d_p^2 \frac{\rho_p}{18\mu} \quad (1)$$

Where:

d_p is the diameter of seeding particle.

ρ_p is the density of seeding particle.

μ is the viscosity coefficient of air.

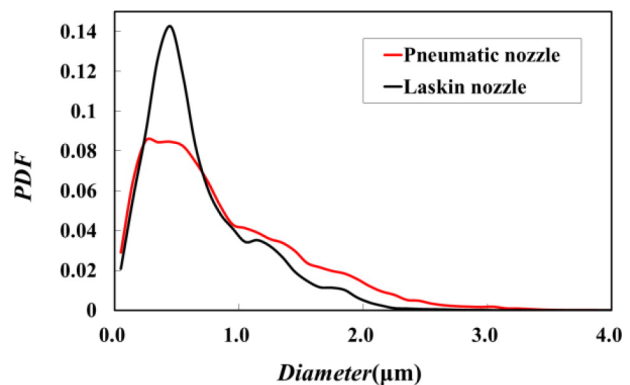


Figure 7. Probability density functions of particle diameter.