

Development of Large-scale PIV Measurement Technique

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ABSTRACT

Particle Image Velocimetry (PIV) is one of the techniques used to experimentally clarify fluid flow phenomena. The advantage of PIV is the ability to non-intrusively measure the instantaneous velocity vectors of a flow field at multiple points. The flow field around an actual vehicle has large-scale flow structures, and requires a wide measurement area. A large-scale PIV measurement technique was developed that can measure this type of large-scale flow field.

An index capable of quantitatively evaluating the quality of the measurement was introduced, and the relationship between this index and the measurement accuracy was clarified. In addition, a seeding device that enables temporally and spatially uniform seeding of particles to the flow field, and a method to decrease laser light reflection were developed. Application of these technologies realized PIV measurement capable of evaluating an instantaneous velocity field over the large scale of 1.7 m x 1 m. A scanning system and integrated measurement software were also constructed, enabling multi-section measurement in a short time.

1. Introduction

Honda products center on mobility, and have a strong relation to fluid flow. It is thought that the need to examine and control various fluid flow phenomena will further increase in the future, from the viewpoint of enhancing fuel economy and comfort. Hot-wire anemometers, pitot tubes and other methods that insert probes for measurement are widely used as flow field measurement techniques to experimentally clarify flow field phenomena. However, there is the issue that probe insertion affects the flow field, making it a challenge to measure the original flow field. Laser Doppler Velocimetry (LDV) is a non-intrusive measurement method that does not use probes, but as measurement is performed at single points, a large number of measurement points is required to understand the entire flow field.

Particle Image Velocimetry (PIV) measures the velocity of a flow field by irradiating laser light into a seeded flow field, using cameras to image the scattered light reflected from the particles, and analyzing the particle images. By using this type of measurement method, PIV can non-intrusively and simultaneously measure the instantaneous velocity vectors of a flow field at multiple points. This makes it easier to understand the entire flow field, so PIV has come to be widely used in recent years.

However, PIV requires much measurement know-how, and trial and error is needed before accurate measurement is possible, so PIV can hardly be called an established measurement technology.

In addition, when measuring the flow field around an actual vehicle, the flow structure has a large scale, so wide-area measurement is desired. One example of this type of measurement is measurement over a 0.3 m x 0.3 m area by Pininfarina S.p.A.⁽¹⁾ However, when measuring an even wider area, the seeding method and the method for acquisition of clear particle images are issues. Therefore, this study organized and addressed these and other issues to establish a large-scale PIV measurement technique that can measure wide areas. This paper reports these technical contents.

2. Overview of PIV Measurement

PIV measurement seeds a flow field with micro particles that sufficiently track the flow, and irradiates the flow field with sheet-shaped laser light (light sheet) two times at a small time difference. This light sheet is reflected by the seeding particles, producing scattered light that is captured by imaging equipment such as a CCD camera. The particles move together with the flow, so the particle positions change in the two particle images shot at a small time

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difference. This particle movement amount is obtained from the two particle images, and the velocity is calculated from the movement amount and the imaging time difference. Figure 1 shows a typical PIV measurement system configuration. Figure 2 shows an example of the obtained particle images.

The method used to calculate the velocity from the

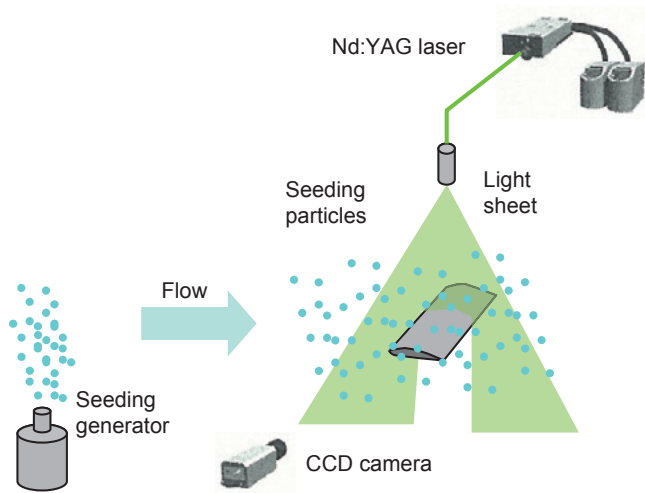


Fig. 1 PIV system

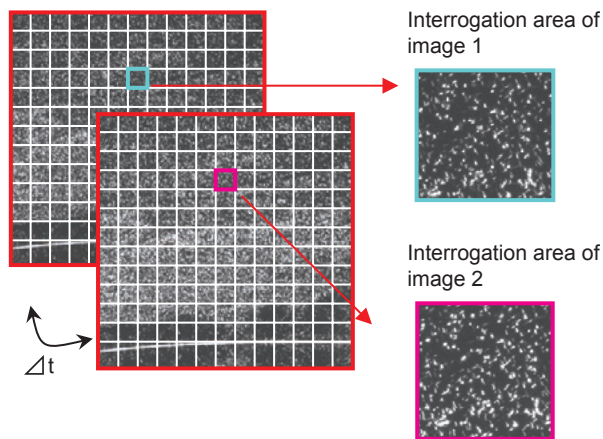
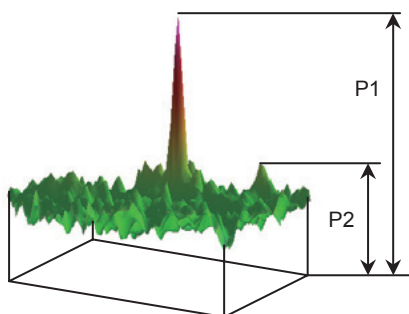


Fig. 2 Example of particle images



P1: First peak value
P2: Second peak value

Fig. 3 Correlation map

pair of particle images shot at a small time difference is as follows. First, the paired particle images are each divided into lattice-shaped interrogation windows. Correlation values are obtained as the movement amount parameter, from the distribution of brightness values (light intensity) within the interrogation windows that correspond to the same positions in both particle images. These correlation values are calculated using convolution operations and FFT. Figure 3 shows an example of an obtained correlation value distribution map. The movement amount that results in the maximum correlation value (first peak value) is used as the average movement value of the particle group within that interrogation window. Next, a velocity vector is calculated from that movement value and the time difference. The two-component velocity field within a two-dimensional plane can be visualized quantitatively by applying this method to all of the divided interrogation windows. In addition, a three-component velocity field can be measured (stereoscopic PIV) by acquisition of particle images using stereoscopic photography with two cameras, and performing the appropriate camera calibration.

This is the PIV measurement principle, so it is important to acquire clear particle images. This requires much measurement know-how, including seeding methods, laser power, and imaging conditions.

3. Target Values for Large-scale PIV Measurement

Technical development of large-scale PIV measurement was initially promoted by application to the downstream flow after the front tire of an F1 racing car⁽²⁾. Examination of the flow phenomena required a measurement area scale of 1 m x 1 m, so this is set as the measurement area target value.

In addition, the ratio of the number of vectors obtained, excluding error vectors, to the total number of vectors that can be obtained within the subject measurement area was defined as the vector acquisition ratio. This vector acquisition ratio target value was set at 90% or more. Here, error vectors refer to vectors for which the correct movement amount could not be calculated from the particle images. The basis for setting a vector acquisition ratio of 90% or more as the target value is that even when a single error vector point occurs, as long as the vectors for the surrounding eight vector points can be obtained, that error vector can be eliminated and interpolation performed as appropriate using the surrounding vectors.

The PIV measurement procedure consists of acquisition of particle images, transferring the shot images to a PC for analysis, and performing post-processing on the analyzed velocity field. When performing PIV measurement in a wind tunnel, shortening the time required for the series of measurement and analysis operations at the test site is also desired.

Measurement of the downstream flow after the front

tire of an F1 racing car had a low vector acquisition ratio of approximately 20%. In addition, many particle images had to be shot and analyzed to evaluate the average flow field, which took much time.

The measurement and analysis time target value for two-component measurement was set at 20 minutes (excluding the setup time) per measurement section.

In addition, detailed three-component measurement of a flow field requires multi-section measurement. When performing multi-section three-component velocity measurement, wind tunnel operation has to be stopped each time there is work to change the measurement section. Therefore, a system was constructed that can measure ten sections without the need to stop wind tunnel operation during three-component measurement, and the measurement time target value was set at 30 minutes.

4. Technical Issues for Large-scale PIV Measurement

4.1. Quantization of Evaluation Method and Applicable Limits of Measurement Conditions

Particle image quality is important in PIV measurement. Factors thought to determine particle image quality include seeding, laser power, spatial distribution of the light sheet intensity, camera sensitivity, imaging magnification, and the noise level, that is to say the background light and light reflected from the test object. Thus far there was no index to quantitatively evaluate the quality of PIV measurement, so clear guidelines could not be set for the various measurement parameters mentioned above. For this reason, trial and error was needed before measurement could be performed each time the measurement subject or measurement location changed. This made it important to clarify the application limits of the measurement parameters before measurement.

4.2. Reduction of Reflected Light

During PIV measurement, in addition to scattered light reflected from the seeding particles, light sheet reflected from the surface of the test object is also included in the shot images as noise, and may result in a drop in particle image quality. The effects of this reflected light can be reduced by image processing, but when the reflection intensity is high, this may hinder detection of the scattered light reflected from the particles, which is an issue. Figure 4 shows the conventional technique for reducing reflected light. The wall surface is coated with a fluorescent paint that, when irradiated by light, emits light (fluorescence) with a different wavelength than the incident light. This fluorescence is then reduced using a band-pass filter installed in front of the camera (wavelength shift method).

However, even when using this method, some test objects have surfaces that are a challenge to treat directly, so a more general-purpose method to reduce reflected light was needed.

4.3. Seeding

Seeding is an important technique that affects PIV measurement quality, and involves many items that need to be investigated such as the material and diameter of the particles to be used, and the method of seeding the particles to the flow field. Laskin nozzle generators that can atomize fluids such as olive oil, and fog generators that can vaporize glycol-based solvents into particles are commercially available and widely used. Laskin nozzle generators can produce uniform particles with a diameter of approximately 1 μm . In addition, fog generators are able to generate large volumes of particles.

Achieving a uniform temporal and spatial distribution of seeding particles over a wide area is an issue for large-scale PIV measurement. When the particle distribution is temporally or spatially uneven, velocity vectors cannot be obtained in areas that lack sufficient particles, and the vector acquisition ratio drops. A major advantage of PIV measurement is the ability to quantitatively visualize an instantaneous two-dimensional flow field. However, full use cannot be made of this advantage when there is particle unevenness. The commercially available seeding devices mentioned above were unable to address this issue, so efforts were made to develop a new seeding device.

4.4. Acquisition of Clear Images of Particles

To image a wide area, the light sheet should be irradiated over a wide area. Assuming that the same laser device is used, this means that the laser power per unit area drops, and the images of the particles in the shot particle image become unclear. In these cases the error vectors increase and sufficient velocity vectors cannot be calculated. Therefore, acquisition of clearer particle images even at a low laser power per unit area is an issue.

4.5. Shortening Measurement and Analysis Times

The average flow field obtained by the PIV measurement procedure described in Chapter 3 is obtained by averaging multiple instantaneous velocities acquired from a pair of particle images. When these instantaneous velocities have many missing vectors due to error vectors or other factors,

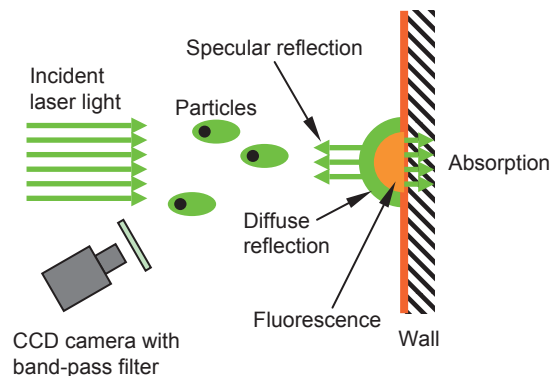


Fig. 4 Schematic view of laser light reflection from fluorescent coated wall

the average number of measurement times, that is to say the number of shot particle images, has to be increased, which increases the measurement and analysis time.

In addition, when the particle image quality is low, image processing is needed before analyzing the particle images, which is also a factor increasing the analysis time.

For these reasons, a method that enables evaluation with a small average number of measurement times without processing images in advance is needed to shorten the measurement and analysis times. Obtaining better quality particle images and increasing the vector acquisition ratio can lead to shorter measurement and analysis times.

When measuring and examining a complex flow field, it is better to understand the three-dimensional flow field, and the results using only a single section are insufficient. In these cases, multiple sections should be measured as described in Chapter 3. Changing the measurement section involves tasks such as setting up the laser optics system and camera and calibrating the camera, and performing these tasks efficiently is an issue.

5. Methods for Addressing Each Issue

5.1. Quantization of Evaluation Method Using the Peak Ratio

Investigations were carried out to address the various issues described in Chapter 4. First, an index capable of quantitatively evaluating the quality of PIV measurement was introduced. Basic tests were performed, and it was found that using the peak ratio as this index enabled quantitative evaluation of the measurement quality. As described in Chapter 2, the velocity vector is calculated from the movement amount, which is the peak correlation value of the light intensity distribution in a pair of interrogation windows. The peak ratio is expressed by the ratio between the first peak value and second peak value of these correlation values (Fig. 3).

PIV measurement was performed using a flow of a known velocity with different measurement conditions, such as the laser power and imaging magnification, to obtain the relationship between the peak ratio and measurement error. The difference between the measured movement amount and the movement amount obtained from the actual velocity was used as the error. Figure 5 shows the relationship between the peak ratio and measurement error. The figure shows the error as the number of pixels.

This figure shows that measurement error increases when the peak ratio is less than 1.2. Therefore, peak ratio is used as an index to evaluate measurement, and velocity vectors with a peak ratio value of 1.2 or less are judged as error vectors.

Use of the peak ratio as an evaluation index enabled clarification of the measurement conditions such as the laser power, imaging magnification, camera lens aperture, and particle density.

5.2. Reduction of Reflected Light by Application of a Fluorescent Sticker

The new technique addressed the issue of reducing reflected light described in Section 4.2, by using fluorescent film with adhesive (fluorescent sticker). This increased the general applicability and effectively reduced reflected light. The basic tests performed to realize this method are described below.

Figure 6 shows a schematic diagram of the test apparatus.

The test apparatus irradiated the test piece with a Nd:YAG laser that emitted light sheet using a cylindrical lens, imaged the reflected light with a CCD camera, and evaluated the light intensity. Three types of coverings were applied to the test piece surface based on the wavelength shift method described in Section 4.2. These were a fluorescent spray (Asahipen Corporation), a fluorescent sticker (Sumitomo 3M Limited), and a matte-coated fluorescent sticker. Material that emitted fluorescent light with a wavelength of 532 nm, which is the second harmonic wave of the Nd:YAG laser, was selected as the fluorescent material. The fluorescent film had a glossy surface, so evaluation was also performed in the matte condition to evaluate the effects of the surface condition on the reflection characteristics.

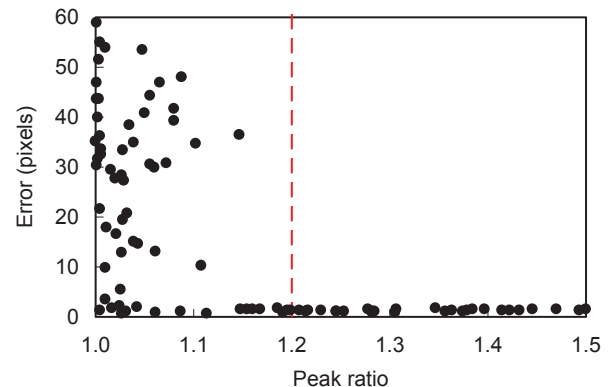


Fig. 5 Relationship between peak ratio and measurement error

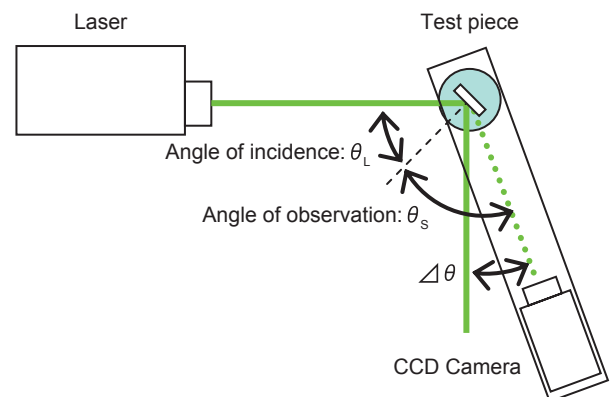


Fig. 6 Schematic diagram of experimental setup for reflection intensity

In actual PIV measurement, the angles at which reflected light is imaged differ according to the shape of the test object and the measurement layout such as the camera position. Therefore, the reflection intensity was evaluated at different imaging angles. Figure 7 shows these results. The figure shows the relationship between the intensity of the reflected light from the imaged test piece and the imaging angle $\Delta\theta$. $\Delta\theta$ is defined as the angle calculated from the difference between θ_s and θ_L in Fig. 6. The reflection intensity of the fluorescent sticker was the maximum at an imaging angle of 0° (mirror reflection), and decreased as the angle increased (diffuse reflection). The figure also shows that the fluorescent sticker had a smaller reflection intensity than the fluorescent spray at angles greater than 0° .

In addition, the matte-coated fluorescent sticker exhibited approximately the same reflection intensity as the fluorescent spray, indicating that the glossy condition of the surface affects the reflection characteristics. The reflection that affects the particle images in PIV measurement is mainly diffuse reflection, so the fluorescent sticker with a glossy surface is the most effective at reducing reflected light. Use of this fluorescent sticker enabled reduction of light reflection from the wall surface to 1/10 compared to the conventional fluorescent spray.

5.3. Development of an Original Seeding Device

A seeding device was developed to address the issues described in Sections 4.3 and 4.4. Development aimed for global seeding that fills the entire wind path area with particles to realize a temporally and spatially uniform particle distribution. This required long-lived particles to help prevent particle extinction during the measurement time. Basic tests were performed on particle life, and the results showed that Dioctyl sebacate (DOS) was suitable as a particle material.

An additional aim was to increase the particle diameter to acquire clearer particle images during large-scale measurement. This is because the intensity of the scattered light reflected from the particles is thought to be proportional to the square of the particle diameter. The AKI D impinging-type pneumatic spray nozzle [H.IKEUCHI

Co., Ltd.] can increase the particle diameter, so this AKI D nozzle was investigated as a device component by comparison with a Laskin nozzle using DOS. A Laskin nozzle and an AKI D nozzle were used to seed DOS inside a compact circular wind tunnel to simulate the particle status in a wind tunnel. The diameter of the particles inside the circular flow was measured by the phase Doppler anemometer. Figure 8 shows the particle diameter distribution for a sample size of 50000 particles. The horizontal axis of the graph shows the particle diameter, and the vertical axis shows the number of particles measured. Note that the vertical axis does not show numbers of particles greater than 150.

This comparison showed that the AKI D nozzle distribution included larger diameter particles than that of the Laskin nozzle. These results indicate that the maximum particle diameter in the circular flow was approximately $4\ \mu\text{m}$. In addition, Fig. 9 compares the peak ratios when PIV measurement is performed using AKI D nozzle particles and Laskin nozzle particles.

This figure shows that the AKI D nozzle particles result in a higher peak ratio. This is thought to indicate that percentage of large-diameter particles increased, which increased the peak ratio.

In addition, PIV measurement measures the movement amount of seeding particles mixed into the flow, so having the particles sufficiently track the flow is important

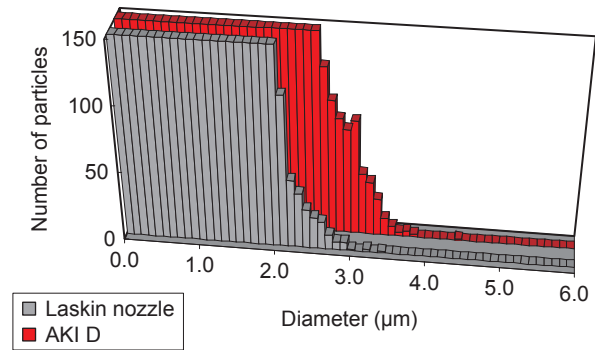


Fig. 8 Histogram of particle diameter

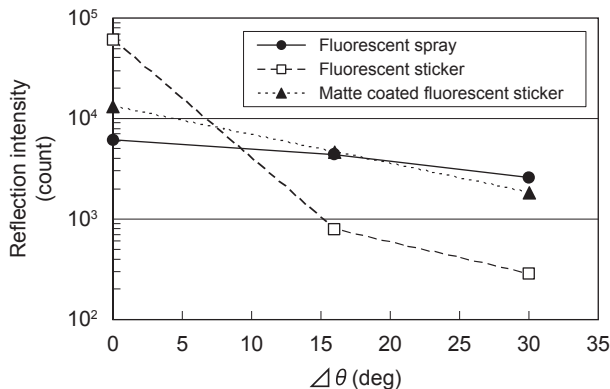


Fig. 7 Comparison of reflection intensity

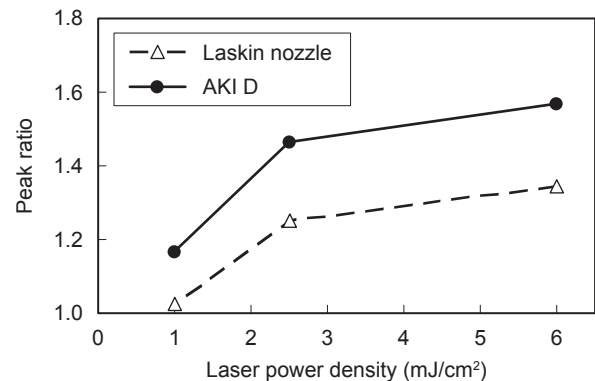


Fig. 9 Comparison of peak ratio

from the viewpoint of accurate flow measurement. Flow tracking performance generally tends to decrease as the particle diameter increases. As mentioned above, the particles sprayed by the AKI D nozzle have a maximum particle diameter of $4\ \mu\text{m}$. Therefore, the flow tracking performance⁽³⁾ of particles of this diameter was confirmed. Figure 10 shows the frequency at which the flow fluctuates and the tracking performance of the particles, using the particle diameter as the variable parameter. The vertical axis of the graph shows the ratio of the particle velocity to the flow velocity. In this figure, for example when the area around a door mirror (typical length 0.2 m) is measured at a flow velocity of 100 km/h, the typical frequency at which the flow fluctuates is thought to be approximately 140 Hz. At this frequency, the tracking error of particles with a particle diameter of $5\ \mu\text{m}$ is approximately 0.2%. This indicates that particles seeded by the constructed device adequately track the flow.

Based on the above results, an original seeding device was constructed using AKI D nozzles. This enabled temporally and spatially uniform seeding, which in turn enabled acquisition of clear particle images with a low laser output per unit area. Figure 11 shows a photograph of the device. The device used four AKI D nozzles with the aim of reaching the particle density required for measurement in a short time. Pressurized air and DOS are supplied to each of the nozzles. The DOS is supplied to the nozzles from a pressurized tank.

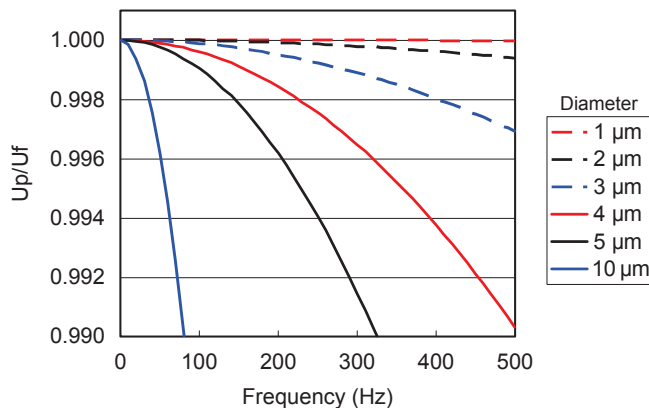


Fig. 10 Velocity lag in periodic air flow



Fig. 11 Seeding system

5.4. Development of an Original Scanning System and Integrated Control Software

When performing stereoscopic PIV measurement as described in Chapter 2, it is important to calibrate the cameras to calculate the three-component velocity using the parallax between the two cameras. This camera calibration is performed using an imaging object (calibration target) with calibration points arranged in a lattice shape. The calibration method consists of setting the calibration target at the measurement position parallel to the light sheet, imaging the calibration target with each camera, and analyzing the images. When performing multi-section measurement, calibration should be performed for each measurement section, which increases the task process time and the measurement time. Therefore, for this technique, a scanning system was constructed to reduce the task process and measurement times. Figure 12 shows this scanning system.

This system places two cameras and a light sheet optical system on a coaxial traverse system, enabling movement to an arbitrary position while maintaining the relative distances between the two cameras and the light sheet. Use of this scanning system enabled multi-section measurement with a single camera calibration. In addition, the scanning system needs to control various devices such as the traverse device, cameras, laser device, and timing controller. Therefore, integrated control software was compiled that controls these devices and enables automated multi-section measurement.

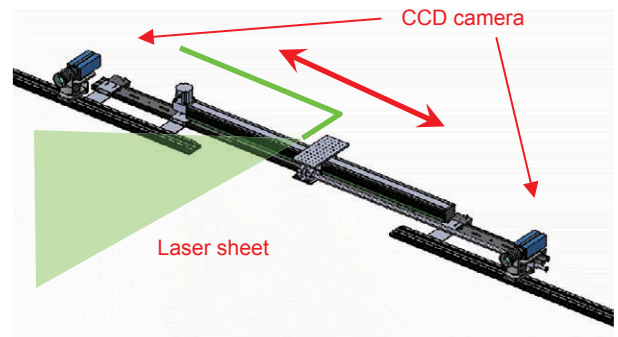


Fig. 12 Scanning system

6. Technical Verification Tests

6.1. Wind Tunnel Tests Using an Actual Vehicle

PIV measurement was performed around an actual vehicle in a vehicle wind tunnel to verify the various technologies described thus far in actual wind tunnel tests. The subject flow was the downstream flow after the door mirror. This flow was measured by irradiating light sheet in a horizontal section from the side and measuring the two-component velocity in the two-dimensional plane imaged from above by the camera.

Light sheet was also irradiated in a vertical section from the side, and stereoscopic PIV measurement was

performed using two cameras positioned on both sides of that light sheet. In addition, scanning stereoscopic PIV measurement was performed by traversing this stereoscopic PIV measurement section in the direction of the flow, and the obtained particle images were analyzed for streamline tracing and to extract the vortical structure and other information.

The light source used for PIV measurement in this vehicle wind tunnel had a wavelength of 532 nm, which is the second harmonic wave of a double-pulse Nd:YAG laser [New Wave Research] with output power of 200 mJ/pulse. The particle images were shot using PCO4000 CCD cameras [PCO AG] with 4008 x 2672 pixels. The laser irradiation and CCD camera exposure timing were controlled by a LC880 timing controller [Labsmith]. The fluorescent sticker described in Section 5.2 was attached to the vehicle body as shown in Fig. 13, as a light reflection countermeasure. The seeding device described in Section 5.3 was installed on the floor sufficiently downstream from the vehicle. When seeding was performed using this seeding device, the particle density required for measurement was reached in approximately 30 seconds. The particle images were analyzed using the PIV analysis software Koncerto [Seika Corporation], and analysis was performed by parallel processing using a PC cluster to shorten the analysis time.

6.2. Measurement Results

Figure 14 shows the measurement results for the instantaneous two-component velocity at the door mirror position.

The measured area was 0.7 m x 0.5 m. Error vectors were eliminated, and the eliminated vectors were interpolated using the surrounding vectors.

The vector acquisition ratio here was 95%, which achieved the initial target. Figure 14 shows that the door mirror wake is quantitatively visualized, and a flow structure of approximately the same scale as the door mirror can be seen.

Figure 15 shows the average instantaneous velocity vectors. These averages were calculated from the results of measuring the instantaneous velocity vectors obtained in Fig. 14 100 times at a frequency of 0.5 Hz. The figure shows that reversing flow occurs in the area immediately

after the mirror. The reversing flow structure seen in the instantaneous velocity field did not appear in the averaged flow field, indicating that this structure is an unsteady flow phenomenon.

In this manner, PIV measurement can be used to evaluate steady flow fields, and also unsteady flow phenomena.

Figure 16 shows the average three-component velocity measurement results obtained by scanning stereoscopic PIV.

The measured area was approximately 1.7 m x 1 m, and ten sections were scanned at a pitch of 60 mm in the flow direction. The measurement frequency and the post-processing of the obtained vectors were the same as those noted previously. The measurement time for each measurement section was 200 s. When the flow velocity was 100 km/h and a door mirror dimension of 0.2 m was set as the typical length, the characteristic time of the flow field was approximately 1/140 s. The measurement time at each section was sufficiently long compared to the characteristic time of the flow field, so the obtained measurement results are thought to be a steady flow three-dimensional three-

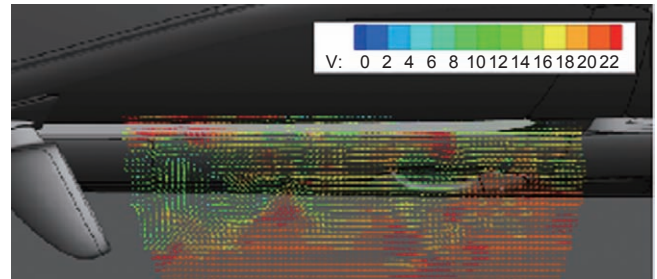


Fig. 14 Measurement result (instantaneous velocity field)

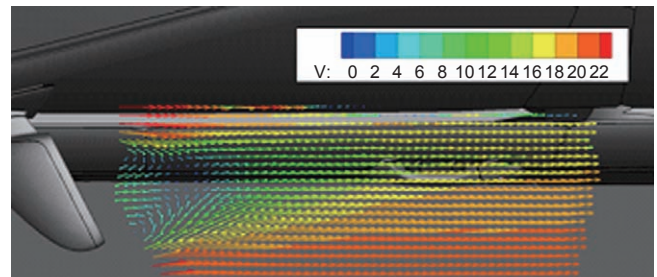


Fig. 15 Measurement result (time averaged velocity field)



Fig. 13 Car with fluorescent sticker

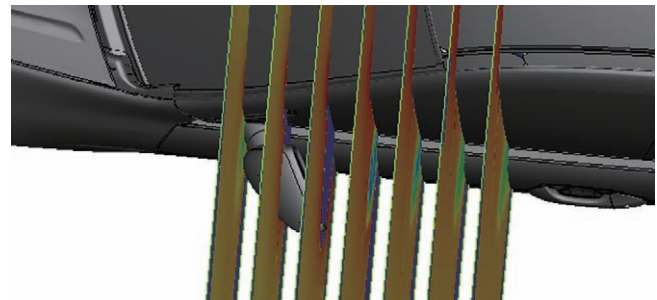


Fig. 16 Measurement result (scanned planes)

component velocity field, and three-dimensional streamline tracing is possible.

Figure 17 shows the streamline tracing results at typical points. This figure shows that the velocity loss area to the rear of the door mirror recovers while swirling in a three-dimensional vortex. Applying the scanning system to this type of complex flow field enables experimentally clarifying actual phenomena, and further deepening understanding of flow phenomena.

6.3. Shortening Measurement and Analysis Times

The PIV measurement of the downstream flow after the front tire of an F1 racing car first performed as described in Chapter 3 had a low vector acquisition ratio of approximately 20%. This meant that 400 instantaneous velocity field measurements needed to be averaged to evaluate the average flow field, so the analysis time was 175 minutes per measurement section.

In contrast, application of the technique described thus far to measurement around the door mirror of an actual vehicle increased the vector acquisition ratio to 95%, which enabled evaluation of the instantaneous velocity fields, and also reduced the number of particle images required for evaluation of the average flow field. The average flow field could be evaluated by averaging 100 instantaneous velocity field measurements as described in Section 6.2. This resulted in a measurement and analysis time of 15 minutes per measurement section, which was less than the initial target of 20 minutes. Realizing temporally and spatially uniform seeding and acquiring clear particle images reduced the number of particle images required, and reducing the reflection intensity reduced the need for image processing before analysis, resulting in a shorter time.

In addition, construction of a scanning system and integrated control software enabled three-component measurement of multiple sections with a single wind tunnel operation. Specifically, the measurement time for ten sections was 24 minutes, which was less than the target of 30 minutes. This was achieved by enhancing the vector acquisition ratio, which reduced the number of particle

images required, and by enhancing operability and enabling automated measurement with the integrated control software.

7. Conclusions

A large-scale PIV measurement technique was developed that can measure large-scale flow fields such as those around an actual vehicle. This technique was verified by measuring the downstream flow after a vehicle door mirror. This technique was able to measure a 1.7 m x 1 m area with a vector acquisition ratio of 95%, thus confirming it as a method for experimentally clarifying the flow field around an actual vehicle.

- (1) The peak ratio was introduced as an index that can quantitatively evaluate the measurement quality. This enabled judgment of error vectors as well as quantitative evaluation of the effects of various measurement parameters on measurement, which helped to ascertain the measurement limits.
- (2) Use of a fluorescent sticker increased general applicability, and realized a method for reducing the light reflected from the test object to 1/10 that of the conventional method.
- (3) A new seeding device was developed that is suited to large-scale PIV measurement. This device realized temporally and spatially uniform seeding and enabled the acquisition of clear particle images at low laser output per unit area, which increased the vector acquisition ratio.
- (4) Increasing the vector acquisition ratio enabled reducing the number of particle images required, and achieved a measurement and analysis time of 15 minutes per measurement section during two-component measurement.
- (5) Construction of a scanning system and integrated control software enabled measurement of multiple sections with a single wind tunnel operation, and achieved a measurement time for ten sections of 24 minutes.

8. Afterword

PIV measurement can be applied to various flow fields, from micro-scale flows to large-scale flows such as reported in this study. The effective use of this PIV technology can help verify CFD and experimentally clarify various fluid flow phenomena. This is expected to enhance performance of machines that are affected by fluid flow, and lead to further development of fluid flow dynamics.

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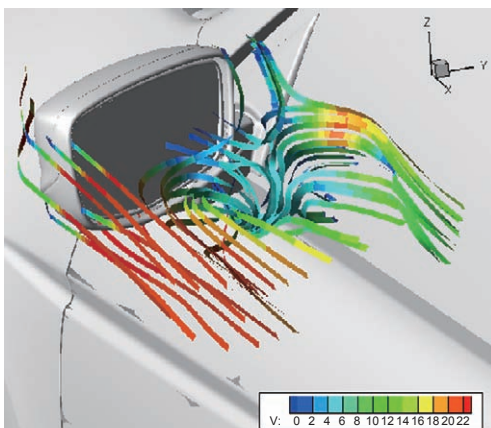


Fig. 17 Streamline around mirror

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