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Dynamic PIV Measurement of a High-Speed Flow Issuing from Vent-Holes of a Curtain-Type Airbag

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Abstract : A curtain-type airbag is a safety device designed to protect passengers from the side collisions of a car. The curtain-type airbag system consists of an inflator, a fill-hose, and a curtain-airbag. The fill-hose is a passageway and distributor of the exploded gases from the inflator to the airbag through vent-holes. Although the design of vent-holes is important for proper deployment of the airbag, it is very difficult to measure the exceedingly high speed flow issuing from the vent-holes by using conventional measurement methods. In this study, we employed a dynamic PIV technique to measure the temporal evolution of instantaneous velocity fields of the flow ejecting from the vent-holes. From the velocity field data measured at a frame rate of 2000 fps, the temporal variation of the volume flux from vent-holes was also evaluated for the diagnosis of airbag performance. The flows ejecting from the vent-holes showed high velocity fluctuations, and the maximum velocity was about 480 m/s. The instantaneous velocity fields in the initial stage showed a swaying motion of a high-speed jet. The accumulated volume flux from the vent-holes was also compared at each vent-hole region.

Keywords : Flow visualization, Fill-hose, Dynamic PIV, Curtain-type airbag.

1. Introduction

According to the USA statistics, 1.7 million airbags were deployed among the 257 million airbags on the road in 2003 (Evans, 2004). This number will increase as the number of installed airbags in vehicles increases. The effectiveness of airbags in reducing fatalities and severe injuries is well documented (Cummings et al., 2002; Zador and Ciccone, 1993). Besides the front airbag systems installed on most automobiles, a curtain-type airbag is increasingly being adapted in deluxe cars to protect passengers from the danger of side impact collisions. The curtain-type airbag system consists of an inflator, a fill-hose, and a curtain airbag. The inflator supplies high-pressure gases to deploy the airbag. Lee at al. (2006) measured velocity fields of the high-speed and high-pressure flows issuing from the exit nozzle of an airbag inflator. The flow ejected from the inflator showed very high velocity fluctuations with a maximum velocity of about 700 m/s. The duration time of the high-speed flow was very short and there was no perceptible flow after 100 ms from the ignition. The fill-hose is a long passageway of the charged gases ejected from the inflator nozzle toward the curtain-type airbags. A proper deployment of the airbag is directly related the flow issuing from vent-holes of a fill-hose. Unfortunately, there is very limited information on the exceedingly high-speed flow issuing from the vent-holes of a fill-hose. In this study, we focused on the high-speed flows ejected from the vent-holes of a fill-hose which would be used for deploying the curtain-type airbag. The whole processes occurred within less than 100 ms from the triggering of the airbag system due to impact. Because of its vigorous action, it is not easy to measure the flow ejected from vent-holes of a fill-hose using conventional flow measurement methods. Optical interferometers or LDV system can be applicable to these flows (Mizukaki, 2007). However, the flow information to be obtained would be qualitatively visualized flow images or point-wise data at several measurement locations. Recently, a dynamic PIV velocity field measurement technique was introduced with the advances of high-speed imaging devices and high-repetition pulse lasers. It is now possible for the dynamic PIV system to get instantaneous velocity field data at a very high time resolution (Etoh et al., 2002). Therefore, the dynamic PIV system is very useful for investigating temporal evolution of turbulent flows, especially the unsteady transient high-speed flows (Hwang et al., 2005). In this study, we applied the dynamic PIV system to measure the temporal evolution of instantaneous velocity field of the high-speed flows ejecting from each vent-hole region of a curtain-type airbag fill-hose. Furthermore, based on the measured flow information, the performance of the tested curtain-type airbag was evaluated.

2. Experimental Apparatus and Methods

Figure 1 shows a photograph of the experimental set-up used in this study with a schematic diagram. A fill-hose assembled with an inflator was installed inside a transparent chamber having a physical size of 0.42 m$^{(W)}$ × 0.72 m$^{(H)}$ × 1.92 m$^{(L)}$. The chamber was made of reinforced transparent acryl and rigid aluminum profiles to endure the ignition shock of the inflator. In addition, the fill-hose model and an inflator were firmly fixed to the chamber with a holder, and heavy weights were put on the top side of the chamber to prevent structural vibration just after ignition. The chamber was designed in consideration of the size of a fully-inflated curtain airbag. A relay switch was used to synchronize the inflator ignition with the dynamic PIV system. When the relay switch receives a 5V DC TTL(transistor transistor logic) signal from the delay generator, it sends the triggering signal of 12V DC to the internal circuit of the inflator. The fill-hose model was made of steel pipe for a strong fixture. Its length and inner diameter were 900 mm and 38 mm, respectively. The diameter and location of each vent-hole are the same as those of the real standard fabric fill-hose. The 2-vent-hole, 1-vent-hole and 4-vent-hole regions correspond to the rear seat, B-pillar and front seat, respectively. The diameter of each hole in the 4-vent, 2-vent, and 1-vent-hole regions are 18, 15 and 12 mm, respectively.

Olive oil droplets generated by a Laskin nozzle were used as tracer particles. The transparent test chamber was filled with olive oil particles before the experiments. For high-speed flows, the lag velocity of tracer particles should be considered. The lag velocity U_s can be estimated as functions of

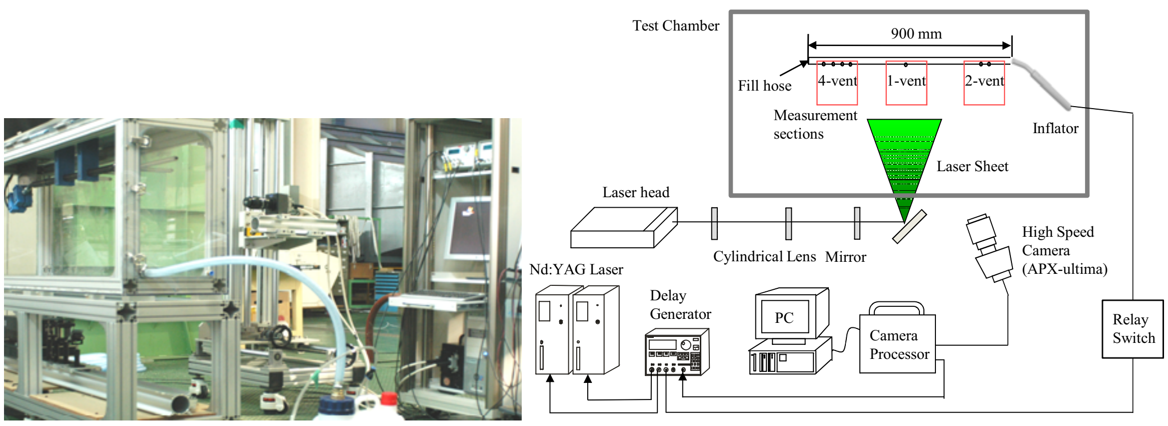

Fig. 1. Experimental setup for dynamic PIV measurements and layout of vent-holes of a fill-hose with three sections of PIV measurement.

particle velocity U_p, particle diameter d_p, fluid viscosity μ, particle density ρ_p, fluid density ρ and particle acceleration a;

$$U_s = U_p - U = d_p^{\,2} \frac{(\rho_p - \rho)}{18\mu} a \tag{1}$$

When the particle density is larger than the fluid density, the step response of U_p follows the exponential law;

$$U_p(t) = U\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right] \tag{2}$$

The relaxation time τ_s is given as;

$$\tau_s = d_p^{\,2} \frac{\rho_p}{18\mu} \tag{3}$$

Strictly speaking, the above equations are not easy to solve because the high-speed flow does not follow the Stokes drag law. In addition, U_p would not simply decay in the form of an exponential function. Despite of these difficulties, the relaxation time τ_s has been usually used to measure the velocity balance between the tracer particles and working fluid. In this experiment, the tracer particles employed have a mean diameter of 2 ~ 3 µm and the corresponding relaxation time are about 10 ~ 25 µs (Lee, 2005). In addition, the compressibility effects would arise in this kind of high-speed flows. In the lag velocity in the equation (1), the fluid density varies due to the compressibility effects. However, since the fluid density is relatively negligible compared to the particle density, the relaxation time does not differ so largely. Therefore, we assumed that the tracer particles follow the high-speed flows in this experiment. The tracer particles were illuminated by a thin laser light sheet of approximately 1mm in thickness, which was collimated by passing several cylindrical lenses and a mirror. The laser light sheet was aligned to pass the center line of the vent-holes of the fill-hose.

The dynamic PIV system employed in this study consists of a high-repetition rate Nd:YLF laser (Pegasus), a high-speed digital camera (Photron APX-ultima), and a delay generator of high accuracy (BNC565). The resolution of the high-speed camera was 1024 × 1024 pixels. The physical size of the measurement area was 146 × 146 mm^2. The corresponding average pixel displacement of tracing particles was about 8 pixels for a flow of about 300 m/s. The proper size of the interrogation window was 32 × 32 pixels with 50 % overlapping. The corresponding physical area represented by one vector was 2.28 × 2.28 mm^2. This kind of low spatial resolution was inevitable under the conditions of large measurement sections and high-speed flows. Although the spatial resolution of PIV measurements is relatively low, the results provide more information than that of point-wise measurements such as LDV or hot-wire. The flow images were captured at 2000 fps (frame per second) and a two-frame cross correlation algorithm was employed to extract velocity vector fields. Therefore, instantaneous velocity fields were obtained at a time interval of 1 ms.

3. Results and Discussion

3.1 Instantaneous Velocity Fields

Figure 2 shows the temporal variation of instantaneous velocity fields in the 4-vent-hole region of the fill-hose. Velocity vectors are represented as arrows at each grid point and color contours indicate the magnitude of vertical velocity component. The fill-hose with vent-holes are indicated as black band on top of each figure. The flow moves from right to left inside the fill-hose model. The high-pressure air is ejected in the downward direction through each vent-hole. At the moment of ignition, it was difficult to extract velocity vectors in the region just near the vent-holes because the flow images were too bright and saturated in gray level due to the exhaust gas from the vent-holes.

At t = 5 ms, the area of high-speed flow faster than 300 m/s is wide and the local maximum velocity is about 480 m/s. Among the four vent-holes, the last vent-hole located near the left-end part has a slightly smaller ejecting flow velocity, compared to the other vent-holes. At t = 10 ms, the area of relatively high-speed flow faster than 300 m/s was still widely distributed. Because the flow ejected from the 4-vent-hole region maintains high speed in a wide area, it may contribute mainly to the airbag inflation. With a lapsed time of t = 20 ms, the high-speed flow area where the speed is above 300 m/s diminishes greatly. In addition, the oblique direction of ejecting flow is changed to a vertically downward direction. The momentum balance between the flow reflected from the end of the fill-hose and the flow incoming from the inflator at this vent-hole region seems to cause the vertical ejecting flow. The speed of flow issuing from the left vent-holes is faster than that of the right vent-holes. This results from the high pressure difference between the fill-hose inside and the outside ambient in the left side vent-holes, induced by the reflected flow.

At t = 30 ~ 40 ms, the area of high-speed flow regions is continuously diminished. The area of high-speed flow above 200 m/s is decreased largely comparing with the flow field at t = 20 ms. When the elapsed time from the ignition is beyond 50 ms, the air is ejected with an oblique angle again and

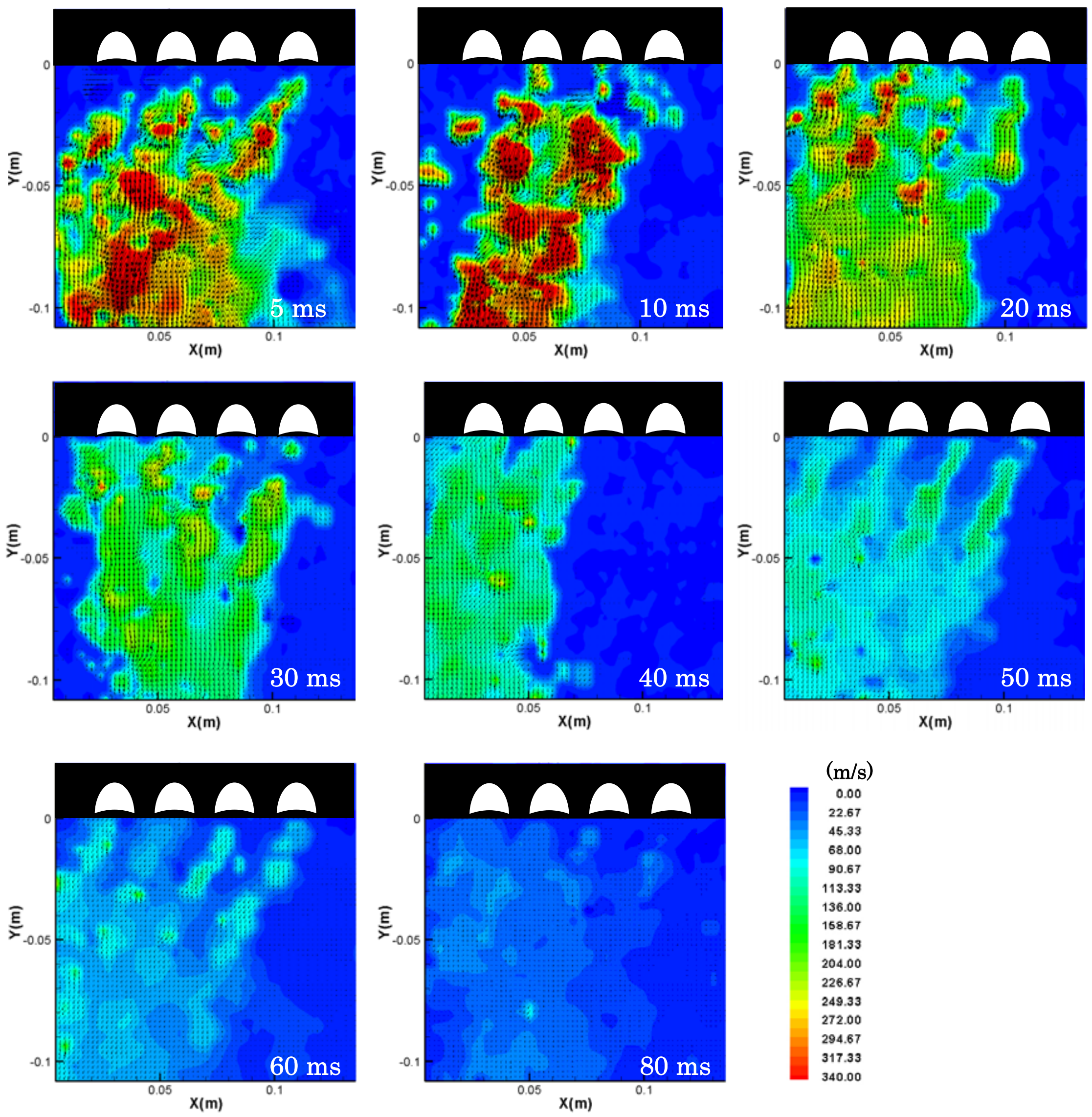

Fig. 2. Temporal evolution of instantaneous velocity field and vertical velocity contours at the four-vent-hole region.

the flow speed is less than 200 m/s in most areas of the measurement plane. The recovering of the oblique flow seems to be induced by the removal of the flow reflected from the left-end of the fill-hose. Beyond the lapsed time of t = 80 ms, the flow ejecting from the 4-vent-hole region is almost disappeared.

Figure 3 shows the temporal variation of instantaneous velocity field in the 2-vent-hole region as a function of time elapsed from triggering the inflator. At t = 5 ms, the flow ejected from vent-holes is inclined about $\theta = 30 \sim 40°$ from the vertical axis. This indicates that the ejecting flow is influenced largely by the horizontal momentum of the high-speed flow passing through the fill-hose. The maximum flow speed is larger than 360 m/s. At t = 10 ms, the oblique angle of the ejecting flow is changed to a nearly normal direction. This indicates that the effect of the returning flow which turns back at the end edge of the fill-hose gradually becomes larger. In addition, the area of high-speed flow is increased compared to that at t = 5 ms. With a lapsed time at t = 20 ms, the area of high-speed flow above 300 m/s is mostly reduced and the range of moderate flow speed is distributed widely. In addition, the direction of ejecting flow turns to a vertically downward direction. The right vent-hole at t = 30 ms and the left vent-hole at t = 40 ms do not show any noticeable ejecting flow. However, at

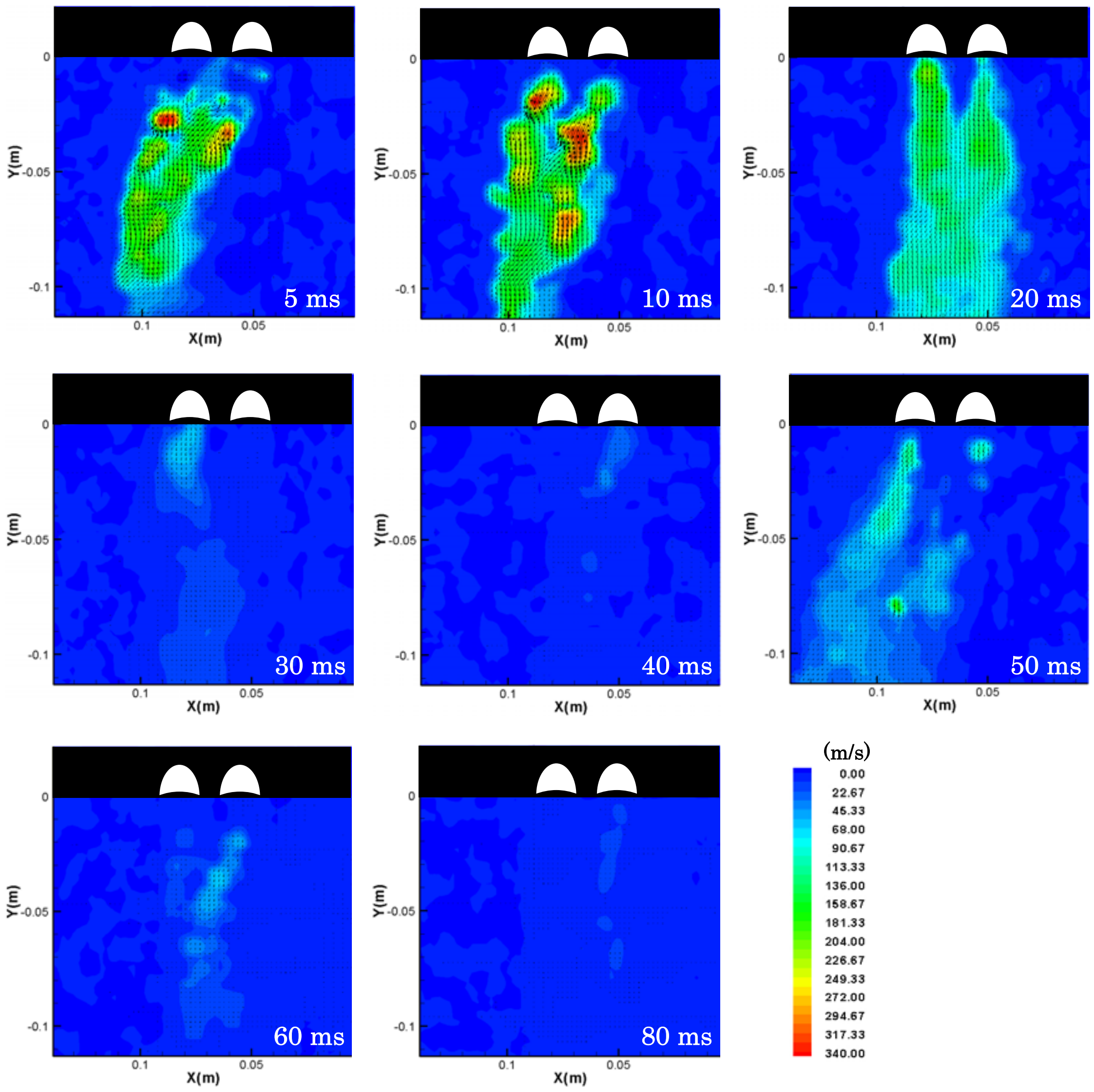

Fig. 3. Temporal evolution of instantaneous velocity field and vertical velocity contours at the two-vent-hole region.

t = 50 ms, the ejecting flow has a remarkable speed of about 100 m/s and some of it is sustained up to t = 60 ms. From these results, we can see that a lump of high pressure gas ejected from the inflator has a kind of oscillatory flow inside the fill-hose. In addition, the lump of air does not pass the 2-vent-hole region at t = 30 ms and 40 ms. Beyond the lapsed time of t = 80 ms, the flow ejecting from the 2-vent-holes region is largely decreased and almost disappears.

Figure 4 represents the variation of instantaneous velocity field in the 1-vent-hole region of the fill-hose with lapsed time. At t = 5 ms, the flow ejecting from the 1-vent-hole region has a local maximum velocity over 490 m/s. In addition, through the whole elapsed time, the ejecting flow shows a weak swaying motion. The direction of ejecting flow is inclined about θ = 10° in the initial stage. At t = 10 ms, the area of high-speed flow is decreased and the momentum of ejecting flow is rapidly reduced. As a consequence, the flow shows the typical velocity distribution of a normal jet with a small jet width. At t = 20 ms, the direction of the ejecting flow is nearly aligned with the vertical direction and the flow maintains its initial high-speed up to far downstream region. With the time elapsed, the ejecting flow gradually disappears at t = 30 ms. At t = 40 ms, however, the high-speed flow of about 200 m/s is ejected once again from the 1-vent-hole region. Nonetheless, there is no more indication of the ejecting flow from the 1-vent-hole region after t = 60 ms.

3.2 Comparison of Volume Flux

The vertical velocity component at the middle height of the measurement plane is extracted from the instantaneous velocity field data and is multiplied with the unit area to calculate the volume flux at the middle height. As shown in Fig. 5, after sending the triggering signal to the inflator, the flow starts to eject about 1.5 ms later in the 2-vent-hole region. It is about 3 ms in the 4-vent-hole region and 4 ms in the 1-vent-hole region. The volume flux was normalized with the maximum volume flux of the 4-vent-hole region.

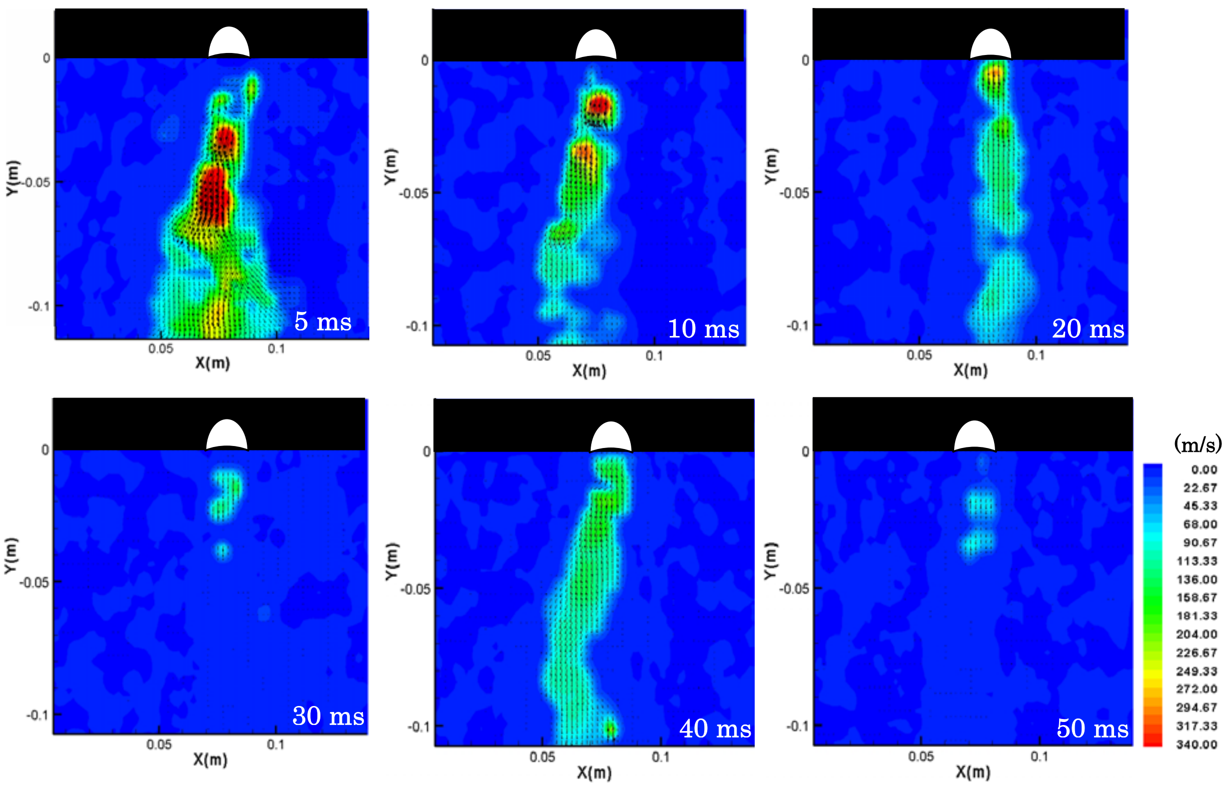

Fig. 4. Temporal evolution of instantaneous velocity field and vertical velocity contours at the one-vent hole region.

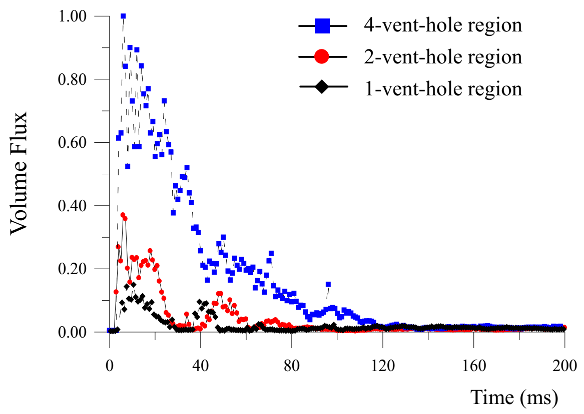

Fig. 5. Variation of volume flux with time.

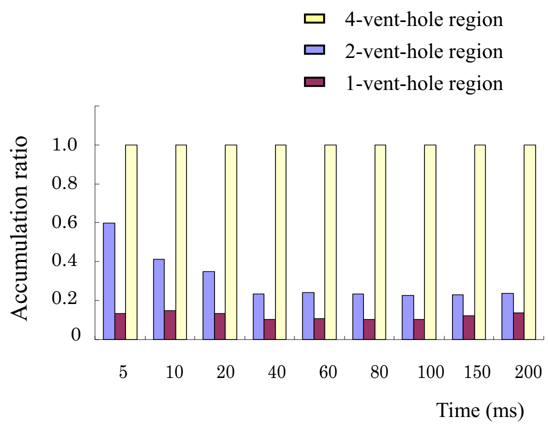

Fig. 6. Relative fraction of accumulated flux from each vent hole region.

The volume flux from the 2-vent-hole region is much larger than that of the 1-vent-hole region. In addition, within the initial 20 ms after igniting the inflator, the flow ejected from each vent-hole shows large velocity fluctuations. The speed of ejected flow is rapidly reduced in the initial period of time. When the time elapsed is beyond 30 ms, there is no distinguishable large difference in the pattern of volume flux between the 1-vent and 2-vent-hole regions. At t = 40 ms, the flow is ejected again from the vent-holes. The re-starting time shows a small difference of about 3ms between the 2-vent and 1-vent-hole regions. There is no perceptible flow motion after 80 ms. In the 4-vent-hole region, the initial volume flux is very large. The ejecting volume flux decreases rapidly with large fluctuations up to t = 40 ms. Thereafter, it decreases gradually and shows small rise-and-fall swaying phenomena several times. From these results, we can see that the total volume of gas flow ejected from the three vent-hole regions was mainly ejected up to t = 40 ms, and then the decreasing rate follow an asymptotic approach.

Figure 6 shows the accumulated flow from the 2-vent and 1-vent-hole regions with respect to that of the 4-vent-hole region as a function of time elapsed. The accumulated volume flux is evaluated by integrating the flow rate with the time interval. During the whole deployment process, the accumulated flow from the 1-vent-hole region occupies only about 10-13 % of that of the 4-vent-hole region. For the case of the 2-vent-hole region, the accumulated flow is about 60 % of that of the 4-vent-hole region. However, the ratio of the accumulated flow of the 2-vent-hole with respect to the 4-vent-hole region is reduced gradually and has a nearly constant value of 23 % after t = 40 ms. Finally, the flow ejected from the 4-vent-hole region occupies about 70 % of the total accumulated flow. In general, because the flow ejected from the 4-vent-hole region is larger than the other vent-hole regions, it is natural to expect that the airbag compartment of the 4-vent-hole region would be deployed rapidly than the other two airbag compartments. In addition, although the volume flux is smaller than other compartments, the 1-vent-hole region seems to work properly, because the main purpose of the 1-vent-hole region is to maintain a good shape of the curtain airbag during deployment in the region between the 2-vent-hole and 4-vent-hole regions. The ejected flow from the 1-vent-hole region shows a steady accumulation rate (about 13 %) in the whole process. However, the 2-vent-hole region seems to have a room for further improvement, because the relative ratio of flow accumulation is decreased in the initial period of time and sustains a low value as the time goes by.

4. Conclusion

In this study, a dynamic PIV system was employed to investigate the flow issuing from vent-holes of a fill-hose of a curtain-type airbag by measuring the temporal evolution of instantaneous velocity field at each vent-hole region. Due to momentum balance and pulsating flow inside the fill-hose, the direction of the flow ejecting from the vent-holes was changed from an oblique to a downward direction with lapse of time. In the 4-vent-hole region, the flow speed was faster than 480 m/s with large velocity fluctuations in the initial stage. In addition, the flow ejecting from the 4-vent-hole region occupied about 70 % of the total volume flux. As a consequence, the deployment of the 4-vent-hole region for a front seat passenger was faster than the 2-vent-hole region for back seat. Beyond t = 40 ms, the flow ejecting from each vent-hole region is decreased significantly. The volume flux of the flow ejecting from the 1-vent-hole region was only about 13 % of the total volume flux in the whole deployment process. This indicates that the 1-vent-hole region was designed for proper deployment of the curtain airbag. However, because the flow ejecting from the 2-vent-hole region occupied only about 20 % of the total volume flux, it seems to have a room for further improvement. This kind of experimental study using a dynamic PIV system would be useful to design a new airbag system and to enhance its performance.

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