Application of stereo PIV to the 70° delta wing at subsonic speed

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Abstract. A stereo PIV technique is utilized for the analysis of the flow field over a 70° delta wing. Instantaneous velocity vectors are measured at a series of stations in the chordwise direction. The angle of attack from 0° to 45° are investigated with the free stream velocities of 20, 30, 40, 50 and 60 m/s, respectively. The velocity measurements conducted in a small-sized subsonic wind tunnel (1.8m×1.4m) at China Aerodynamics Research and Development Center (CARDC) are compared with the previously obtained PSP results. The comparison shows a good agreement with each other, providing the validity of the PIV technique as well as indicating its effectiveness to investigate complex flow fields in a fairly large-scale wind tunnel facility.

1. Introduction
The delta wing is a common layout of modern fighters and drones, with a profound background in engineering applications. At subsonic conditions, the flow around the delta wing is typically geometrically simple, but the physical formation mechanism is complex with vortex flow. At a small angle of attack, the delta wing will form a leading edge separation vortex on the upper airfoil and will continue to increase as the angle of attack increases. When the angle of attack exceeds a certain limit, the vortex develops from stable to unstable, from the trailing edge. The vortex rupture gradually occurs. The vortex rupture has a significant impact on the aerodynamic characteristics of the aircraft. In severe cases, it will have a fatal impact on the maneuverability and stability of the aircraft. In the past few decades, many countries have set up related projects to study the vortex structure and formation mechanism of the delta wing, through the development of pressure-sensitive paint technique (PSP), Particle image velocimetry (PIV) technique, and other advanced experimental methods, measured the surface flow field and spatial flow field fine experimental data of the delta wing model, providing a wealth of resources for the comparative analysis and confirmation of CFD software.

Using PIV technology to obtain velocity field information, and then analyzing the surface flow of the delta wing according to the velocity field, not only can avoid the influence of various test devices on the original flow field around the delta wing, realize non-contact measurement, but also possible to measure the transient flow field in real time, which further study the gas flow characteristics of the delta wing surface. The initial development of PIV technology is mainly two-dimensional particle image velocimetry (2D-PIV). The basic principle is to add tracer particles to the flow field, and the particle velocity represents the velocity of the fluid at the corresponding position. The laser sheet source is used to illuminate a test plane in the flow field, and the CCD camera simultaneously records the position of...
the particles in the adjacent two exposures, and the average displacement of the particles at each point in the query area is obtained by the cross-correlation algorithm. With this displacement and the time interval between exposure, the velocity vector of the flow field can be obtained. However, 2D-PIV measures only the in-plane projection of the three-dimensional velocity vector, and there are inevitable errors, which cannot effectively and comprehensively analyze the three-dimensional transient flow field. For stereo PIV system, it is necessary to perform motion analysis on the particle images of two consecutive frames of the left and right cameras. Firstly, the particle images at the same time of the left and right cameras are matched and fused to find the corresponding regions. Then, based on the correlation analysis of the particle images corresponding to different moments of the same camera, the displacement vector information of the particles on the plane can be obtained. Finally, the vector results are obtained. The spatial displacement of moving particles is obtained after 3D reconstruction. Stereo-PIV overcomes the inherent defects of 2D-PIV, and the calculated in-plane stereo velocity field can more realistically reflect the in-plane and out-of-plane flow field structures.

In this study, the velocity vector fields over a 70° sweep delta wing are obtained at a series of stations in the chordwise direction using a PIV system. The test cases were selected on the basis of the previous results of PSP measurements, which were conducted in the same wind tunnel on the same delta wing model. The angle of attack from 0° to 45° are investigated with the free stream velocities of 20, 30, 40, 50 and 60 m/s, respectively. The analysis is focused on the structure and breakdown characteristics of the vortices depending on the angle of attack and the wind speed. The data obtained from the PIV measurements will be used for the validation of a CFD code for the delta wing configuration. Once validated, the PIV technique along with the CFD method will be applied to various test cases for a parameter study.

2. Experiment Scheme

2.1. Wind Tunnel
The experimental apparatus were set up at the CARDC 1.8m×1.4m Low-speed Wind Tunnel. It is a continuous single-return low-speed wind tunnel driven by a fan motor, as shown in Figure 1. The wind tunnel is made of all-steel structure and horizontally arranged. The center of the circuit is 44.5m at long axis and 12m at short axis, and the height of the tunnel is 3m at center axis. The opening test section was used for the tests presented in this paper, which has a maximum wind speed of 80m/s and minimum stable wind speed of 8m/s, the dynamic pressure field coefficient less than 0.5% and the dynamic pressure stability less than 0.005.

![Fig. 1. CARDC 1.8m×1.4m Wind Tunnel](image)

2.2. Test Model and Support Device
The experimental model is a 70° delta wing with a chord length of 298mm and a span of 216mm. Figure 2 shows a picture of the delta wing model used in the present study. There are 76 taps arranged with six profiles on the model surface. In addition to PIV, we are able to perform surface pressure measurement with PSP and electronic scanning valve system.
The support device is a tail support device. Through the pre-bending struts and the extended tail struts, the model is installed in the center of the wind tunnel opening test section in the side belly support mode, and the angle of attack is adjusted by the ground turntable, as shown in Figure 3. The turntable angle is ±180°, and the turntable angle control accuracy is better than 0.02° with the speed of 0.1°~2°/s.

2.3. PIV System
PIV System used in this study consists of a double-pulse Nd:YAG laser with maximum pulse energy of 2×500mJ at a repetition rate of 15Hz, two 12-bit digital CCD with 6600×4400 pixels, a PC software and a synchronization board developed for the system synchronization, control, data acquisition and post-processing. Aerosol Generator was used for the seeding of DEHS particles. The particles were filled in the tunnel beforehand and the generator was turned off during the actual measurements. The schematic view of the experiments set-up is shown in Figure 4.
The delta wing model is mounted on a ground rotary plate. An aluminum profile is mounted on the rotary plate for fixing the cameras and a flexible light arm. The surface of the model has six rows of pressure tap. Our PIV experiment uses these six rows as measuring section, which is convenient for comparison and analysis with surface pressure data.

The viewing angle of the two cameras is ±45° for a good precision of the out-of-plane and in-plane velocity components during stereo PIV measurements. The time separations between both laser pulses illuminating particles recorded for a single velocity measurement are less than 100µs for M=0.15. For velocity measurements such small time delays require a precise triggering of the lasers and a precise synchronization of the cameras’ framing times. The synchronizer used in our experiment is able to generate complex pulse trains with a resolution of 50 ns. The time sequences for PIV must allow for a proper laser operation by firing the flash lamps near by the nominal repetition rate (15 Hz) to achieve a thermally stable operation. The cameras are operated in the double-frame mode and are triggered such that the first and second light pulses expose the CCD within the corresponding framing period.

3. Experimental results and analysis

In order to verify the credibility of our PIV system, series of fixed speed are given by the empty wind tunnel. The velocity fields in the plane are measured through our stereo PIV system, and then compared with the given wind speed. The test include four conditions: 20 m/s, 30 m/s, 40 m/s, 50 m/s. Figure 5 shows the in-plane axial velocity field obtained by the PIV system at each steady wind speed.

Figure 5(a) shows the measurement result of our PIV system at wind speed of 20 m/s, the velocity field is mainly distributed at 19.6 m/s~20.1 m/s. Figure 5(b) gives the PIV result at wind speed of 30 m/s, the velocity field is mainly distributed at 29.7 m/s~30.3 m/s. The PIV result at 40 m/s is shown in Fig. 5(c), the velocity field is mainly distributed at 39.9 m/s~40.8 m/s. Figure 5(d) shows the PIV results at wind speed of 50 m/s, the velocity field is mainly distributed at 48.1 m/s~50.3 m/s. At different given wind speeds, the velocity field obtained by the stereo PIV system is evenly distributed, with only little deviation from the given value, which means the stereo PIV system can be confirmed to have good accuracy.

Fig. 5. Empty wind tunnel velocity fields obtained by stereo PIV
Figure 6 shows a picture captured by the two cameras about the delta wing model and the particles around it during the experiment. It can be seen from Fig.6 that the spatial particles are evenly scattered in the air, and the vortex structure formed on the upper surface of the model is clearly visible. Proving the superior performance of the stereo PIV system from another perspective.

![3D layout with two cameras shooting particle image](image)

Fig. 6. 3D layout with two cameras shooting particle image

![Comparison of velocity field at x/c=0.625](image)

Fig. 7. Comparison of velocity field at x/c=0.625. The initial and final degree of angles-of-attack, 0° and 45°, respectively. The wind speed is 60m/s.
The velocity measurements were made at wing-surface sections of 6 chord positions, x/c=0.25, 0.375, 0.5, 0.625, 0.75 and 0.875. The PIV measurements were repeated four times while changing the free stream velocities from 20 to 60 m/s with the increment of 10 to check the effect of the velocity variation to the formation of the vortex.

To gain a better understanding of the generic flow characteristics, quantitative analysis, using PIV technique on flow planes, was performed for different angle-of-attack. The flow structure is investigated at six different angle-of-attack $\alpha=0°,5°,15°,25°,35°,45°$ with the wind speed of 60m/s. It can be seen from Fig. 7 that at angle-of-attack $\alpha=5°$, the vortex begins to form and the vortex increases with the increase of the angle of attack.

Fig. 8. Repeatability test results at angles-of-attack of 30°. The wind speed is 60m/s.

In order to verify the stability of the stereo PIV system, the repeatability tests are performed on each section during the experiment. Figure 8 gives the repeatability test results at angles-of-attack of 30°. The wind speed is 60m/s and x/c=0.625. The results of four repetitive experiments show that the repeatability at each section are consistent, indicating that the good stability of the stereo PIV system, further proving the separation vortex of the delta wing model is stable.
Figure 9 shows the typical velocity flow field along six different sections, clearly reflecting the development of the main vortex separation zone above the delta wing in the direction of flow. As with the flow field characteristics reflected by the pressure cloud map (PSP), the delta wing has no vortex breaking in the selected direction along the flow direction until the 80% chord length position. At angle-of-attack $\alpha=25^\circ$, $x/c=0.875$, a vortex breakdown can be observed. In the future, we plan to perform CFD calculations on experimental conditions, which could make comparisons with the experimental results.

4. Conclusion
A stereo PIV setup for application to flows in a subsonic wind-tunnel has been described. Measurements were performed above a 70° delta wing in the 1.8m×1.4m Wind Tunnel in CARDC. The PIV system is able to resolve small flow structures which occur close to the model surface. The test cases were selected on the basis of the results of PSP measurements, which were conducted in the same wind tunnel on the same delta wing model. The PSP results cover a wide range of angles of attack giving first information of the flow topology. The angles 5°, 15°, 25°, 35° and 45° were selected for PIV to get more details of the flow field. The combination of both measurement techniques was useful, particularly, in the case of the vortex system. From the pressure distributions it was not possible to gather clearly the underlying flow field, which on the other hand is possible with PIV. This experiment also shows useful interactions between computational and experimental investigations in order to save costs and to reduce efforts.

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