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Effect of Roll Angle Configurations of a Reverse Delta Type Add-on Device on Wing Tip Vortex Alleviation

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ABSTRACT

An add-on device in the shape of a reverse delta has shown the ability to alleviate wake vortices. The present work studies the interaction of the wing tip vortex and the reverse delta type add-on device vortices. This paper looks at the vortex interactions generated downstream of the wing tip in planes perpendicular to the free stream direction and their dependence on roll angles φ at a mean chord-based Reynolds number of $Rec=2.75\times10^5$. The study reveals that the add-on device causes a reduction in the tangential velocity V_θ and vorticity of the resultant vortex by up to 44.1% and 59.4%, respectively. Also, it is found that the resultant vortex core radius increased by 305%. The results indicate that the reverse delta type add-on device implants countersign vorticity into the wing tip vortex and modifies its roll-up process.

1. Introduction

Continuous air traffic growth demands novel ideas to be explored in the aviation industry so as to overcome the problem of hazardous wake vortex encounters. The objective of these novel ideas is to decrease the aircraft spacing during the take-off and landing phases of flight while upholding the same level of safety. Present separation rules are not adequate to deal with the air traffic demands of the future as additional spacing between aircrafts is allowed than is actually required to avoid air traffic accidents as mentioned by Babie [1]. Adding more runways to airports is not a practical solution as most large airports are close to major metropolitan areas where expansion would be difficult and expensive.

Fatal aircraft accidents have occurred at low altitudes during landing approaches due to wake turbulence because of inadequate time and altitude for pilots to recover full control of the low altitude aircraft when they fly into strong trailing vortices of an earlier large aircraft according to Veillette [2]. Since it is impossible to avert aircraft wake vortices, ways of diminishing their strength have to be considered.

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Rossow [3] conducted wind tunnel experiments to determine an ideal location and orientation for a fin design. The experiments revealed that the wake-induced rolling moments could be reduced by a factor of 3 or more by mounting vertical fins on the upper surface of the wing.

Experiments with a variety of fin designs on research plan-forms as well as realistic aircraft wing shapes have been performed. A fin mounted on the suction surface of the wing was used to create small scale instabilities to achieve diffused wakes [4-7].

Ortega *et al.,* [8, 9] performed tow tank experiments using PIV with a rectangular wing equipped with triangular flaps at the tips that extend from the trailing edge. These flaps created a pair of inboard counter-rotating flap vortices with respect to the tip vortices. The flapped wing vortices instigated a rapidly growing instability wherein each flap vortex became entangled with its outboard counterpart in a periodic fashion. As the instability grew rapidly, the vorticity was rendered far less coherent. The results indicate that the instability in the wake of the triangular-flapped wings offers a possible mechanism to reduce significantly the wake hazard problem.

Tests have been conducted to produce a region of strong turbulent flow by adding delta type plan-form spoilers in the vicinity of the outboard flap vortex by Breitsamter [10]. A significant enlargement of the viscous core by 50–90%, a reduction in maximum induced velocities of about 50% and a reduction in the maximum induced rolling moment of about 30% was noted. It was found that the use of delta type spoilers minimally affects the overall flight performance. A maximum lift reduction of 2.9% was recorded for a double delta spoiler configuration.

Differential Flap Setting (DFS) is a passive technique which focuses on upsetting the wake by deploying the inboard and outboard trailing-edge flaps at different angles. Numerous studies focus on DFS as a conceivable mean to lessen the induced rolling moment [11, 12]. DFS increases the number of merging processes (due to an increase in the number of near field vortices) throughout the roll-up process causing the enlargement of the main vortex and reduction of peak cross-flow velocities. Differential Spoiler Setting (DSS) technique has revealed similar results [13, 14].

Lee *et al.,* [15] have examined a 65° sweep reverse half delta wing (RHDW) with zero deflection as a device mounted on the wing tip to control and reduce the strength of wing tip generated vortices of a semi-span (*b*) rectangular NACA 0012 wing.

Such reverse delta type add-on device studies suggest that they can be used in vortex alleviation [16-18]. The add-on device vortices appear to instill counter-rotating vortices into the vortices generated by the wing tip and flap-tip and alter the process of vortex roll up. These vortex interactions form a much larger spread-out resultant vortex with reduced rotational velocity and vorticity.

The present work investigates the capability of a reverse delta type add-on device at roll angles in alleviating the wake vortex. This investigation is a continuation of the wake vortex alleviation studies previously carried out by the author [16-18].

2. Methodology

2.1 The Experimental Model

Figure 1 shows the NACA 23012 wing model with all dimensions and details, while the add-on device dimensions (mm) are shown in Figure 2. The schematic of the angle variation of the add-on device, while it is mounted on the wing, is shown in Figure 3.

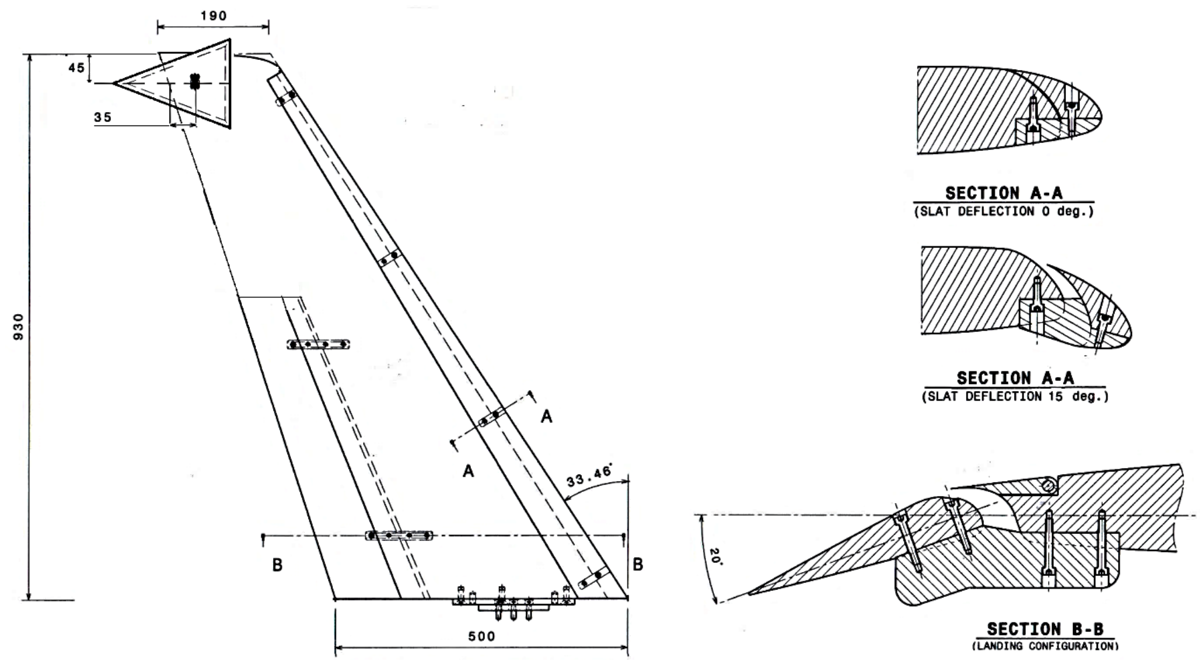


Fig. 1. Schematic diagram of the L-rdw attached to the wing model

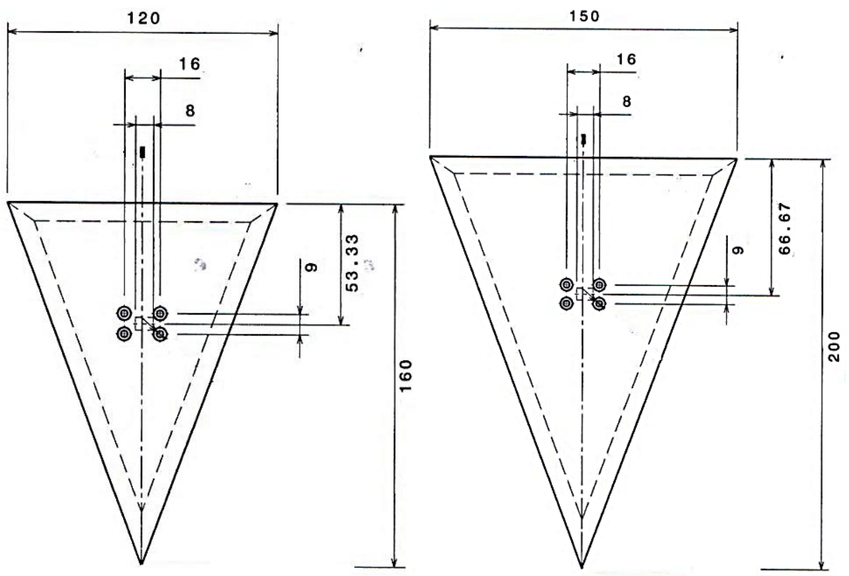
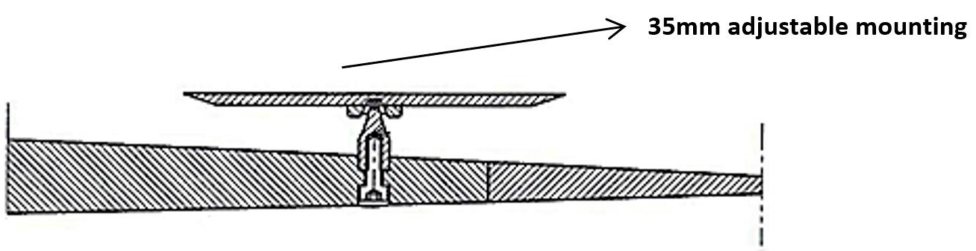


Fig. 2. Schematic diagram of the S-rdw and L-rdw



(ROLL ANGLE VARIATION)

Fig. 3. Schematic diagram showing the mechanism for roll angle variation of the add-on device

2.2 The Wind Tunnel Setup

The whole setup of the experiment in the wind tunnel with wing and PIV setup is shown in the schematic in Figure 4. The direction of the flow is in the x-direction while the PIV camera is located behind the wing to capture the vortex of the wing tip. The laser sheet is in the xy-plane direction. The PIV camera will capture the flow particles injected into the wind tunnel simultaneously as the laser sheet is fired. The x, y, and z coordinates refer to the stream-wise, span-wise, and transverse coordinates, respectively.

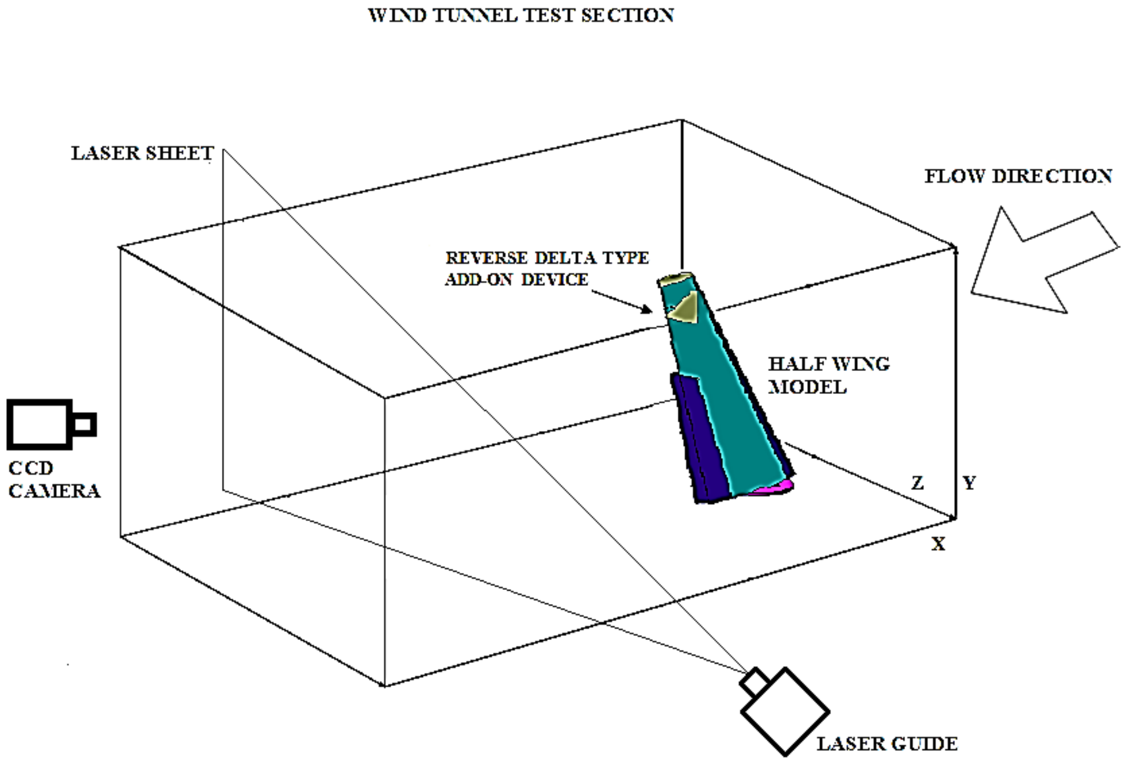


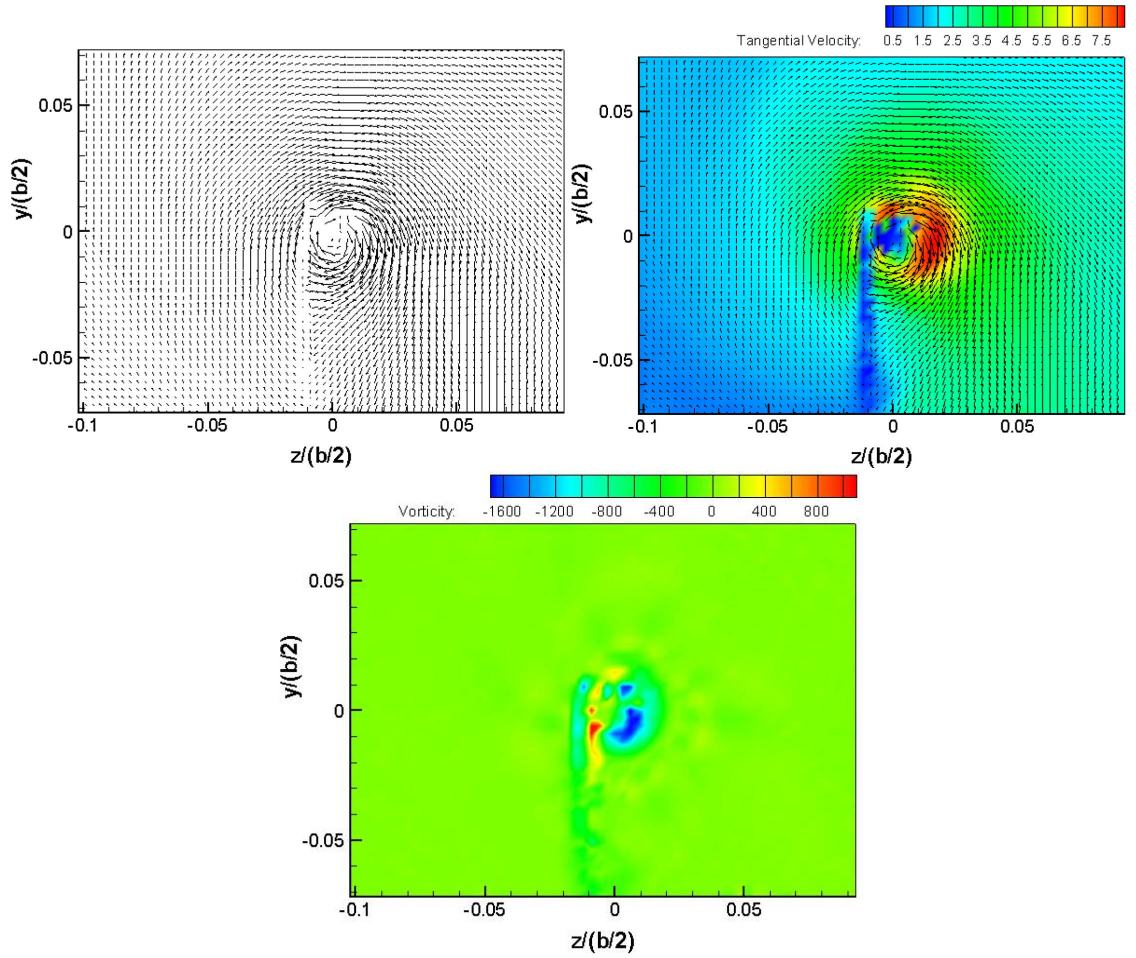
Fig. 4. Schematic diagram of the experimental setup in the wind tunnel

3. Results

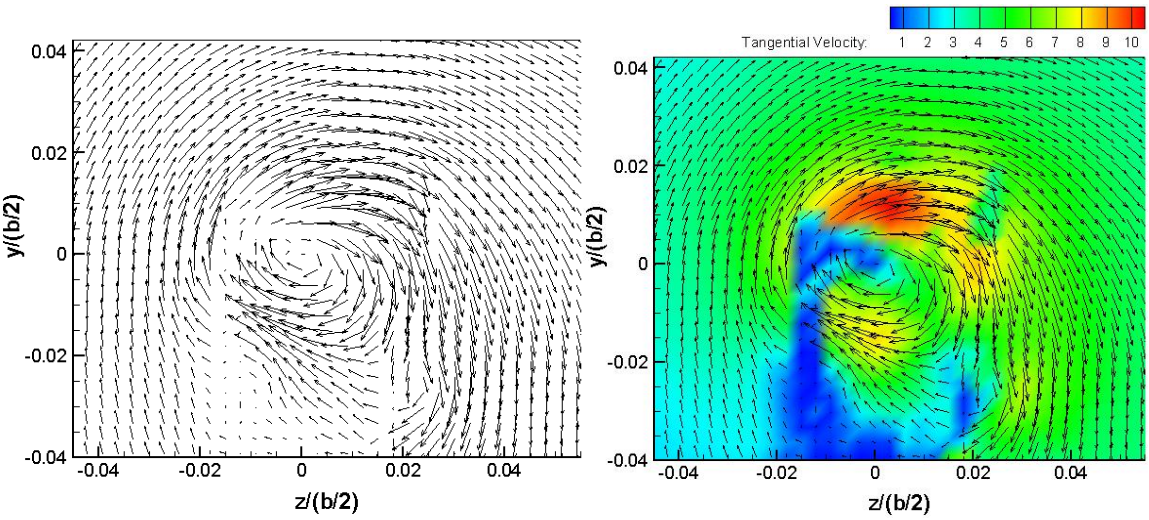
The purpose of the half-span wing model - reverse delta type add-on device configuration is to investigate if the vortices shed by the device at various roll angles are able to instill countersign vorticity into the wing tip vortex and alter the process of wing tip vortex roll-up. The vortices generated by the add-on device and the wing tip are expected to merge downstream and instigate significant wake vortex alleviation. A vortex with a diffused core at the same point has a lower vortex strength and is weaker in magnitude.

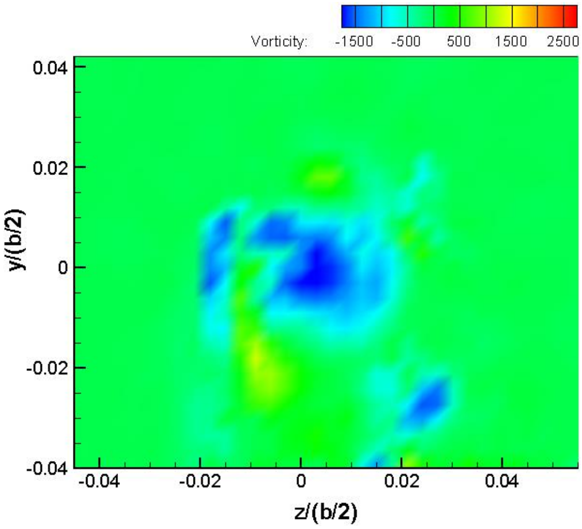
Figures 5 to 8 show the velocity vectors, tangential velocity magnitude, and vorticity magnitude of the High Lift Configuration case (HLC) with and without a reverse delta type add-on device mounted near the wing tip. The flow field consisting of velocity vectors, tangential velocity magnitude, and vorticity are presented at four locations downstream of the wing tip; $x/(b/2)$ = 0.021, 0.548, 1.075, and 2.387. This flow field data will determine if the vortices generated by the merging of the vortices created by the add-on device and the wing tip result in a weaker vortex.

Figures 5b and 5c show that the add-on device vortices merge with the wing tip vortex of the base wing. Two vortex cores are clearly visible in Figure 5c. One vortex core is that of the wing tip vortex and the other vortex core is of the add-on device. The tangential velocity and vorticity magnitudes are higher than the HLC because the inclusion of the add-on device accelerates the flow in the vicinity of the add-on device. Instabilities (counter-sign vorticity) are generated as a result of the mixing of the co- and counter-rotating vortices in the flow field downstream of the wing. This counter-sign vorticity grows into the resultant vortex, resulting in a weaker and diffused resultant vortex. From Figures 6-8, the add-on device cases show that the vortex core dimension has increased, the magnitude of the tangential velocity and the vorticity has decreased significantly compared to the HLC case between downstream planes 1 to 4.

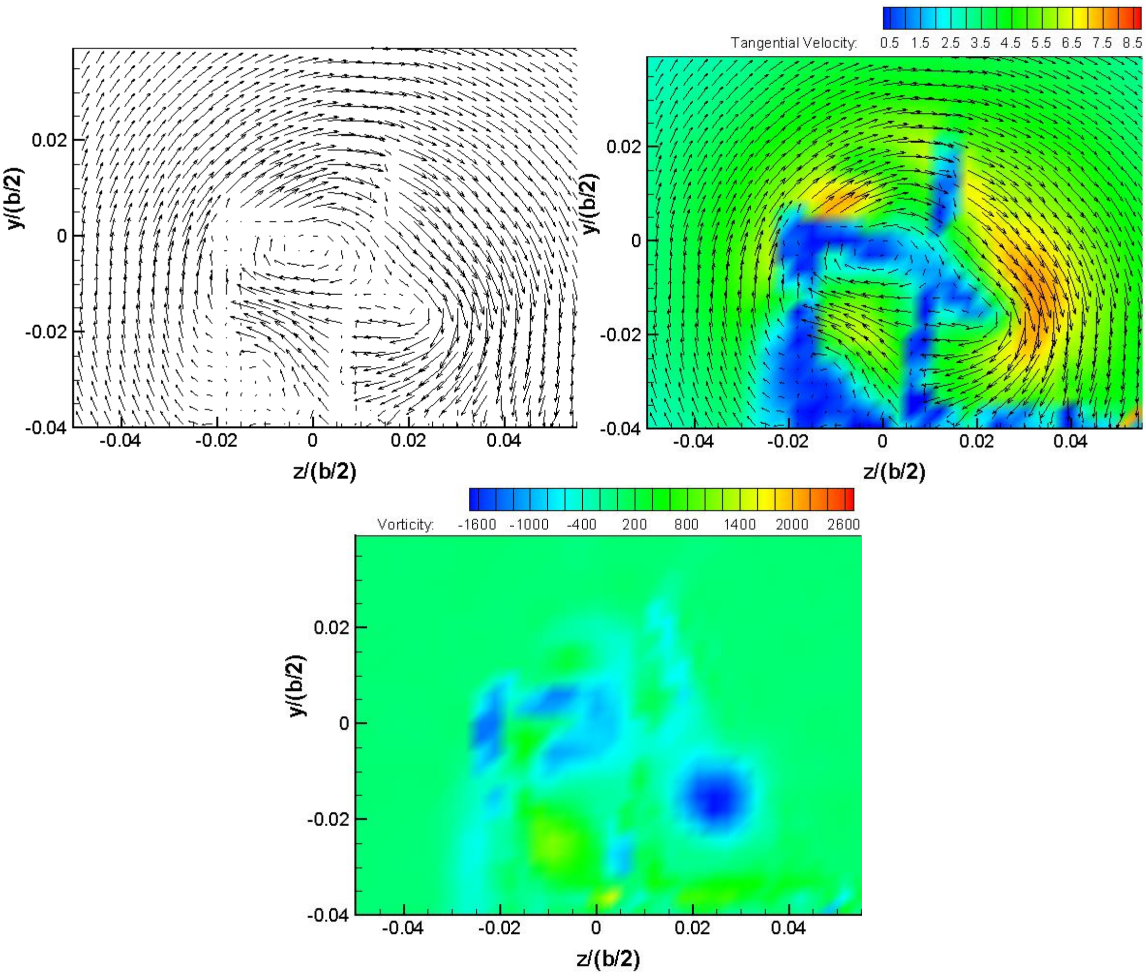


(a) HLC case, α = 7.7°, downstream location x/(b/2) = 0.021, V_∞ = 12 m/s



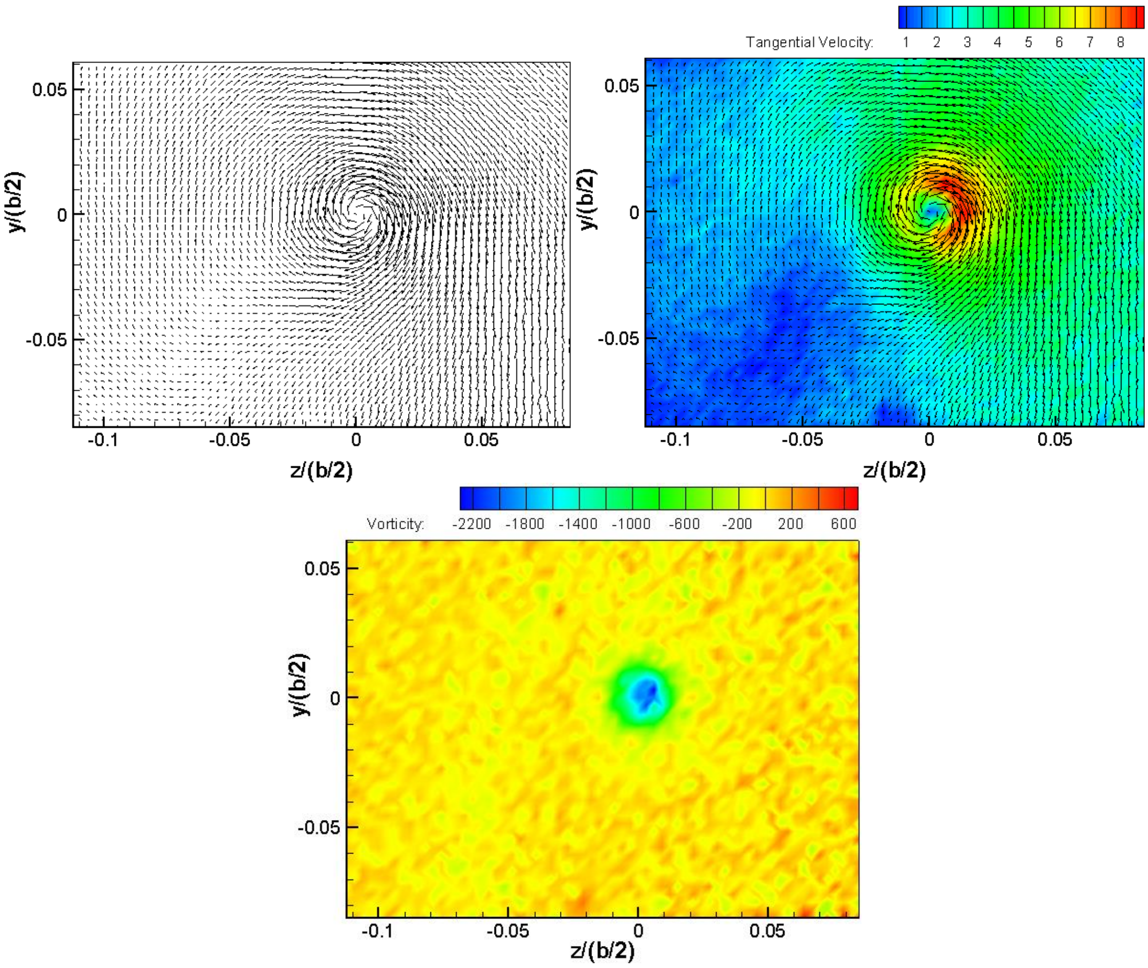


(b) HLC with S-rdw, α = 9.7°, $\varphi_{S\text{-rdw}}$ = -30°, downstream location *x*/(b/2) = 0.021, V_∞ = 12 m/s

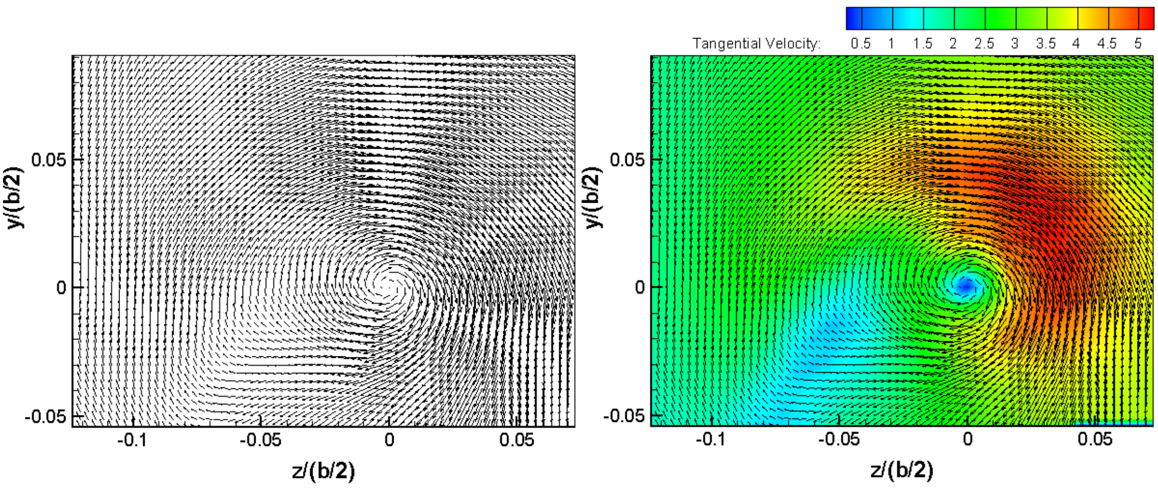


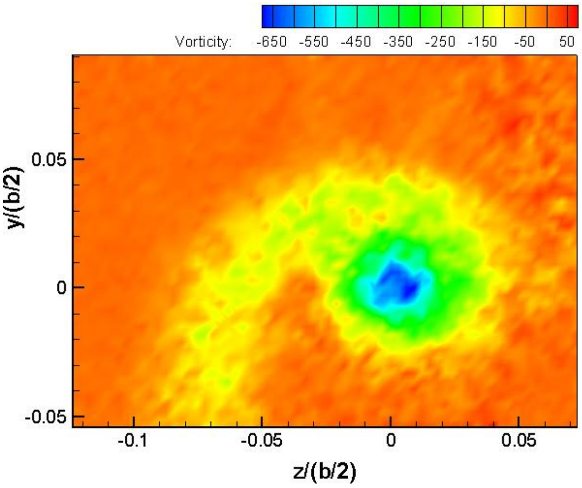
(c) HLC with L-rdw, α = 9.7°, $\phi_{L\text{-rdw}}$ = -30°, downstream location *x*/(b/2) = 0.021, V_∞ = 12 m/s

Fig. 5. Velocity vectors, tangential velocity magnitude and vorticity magnitude at downstream location *x*/(b/2)=0.021

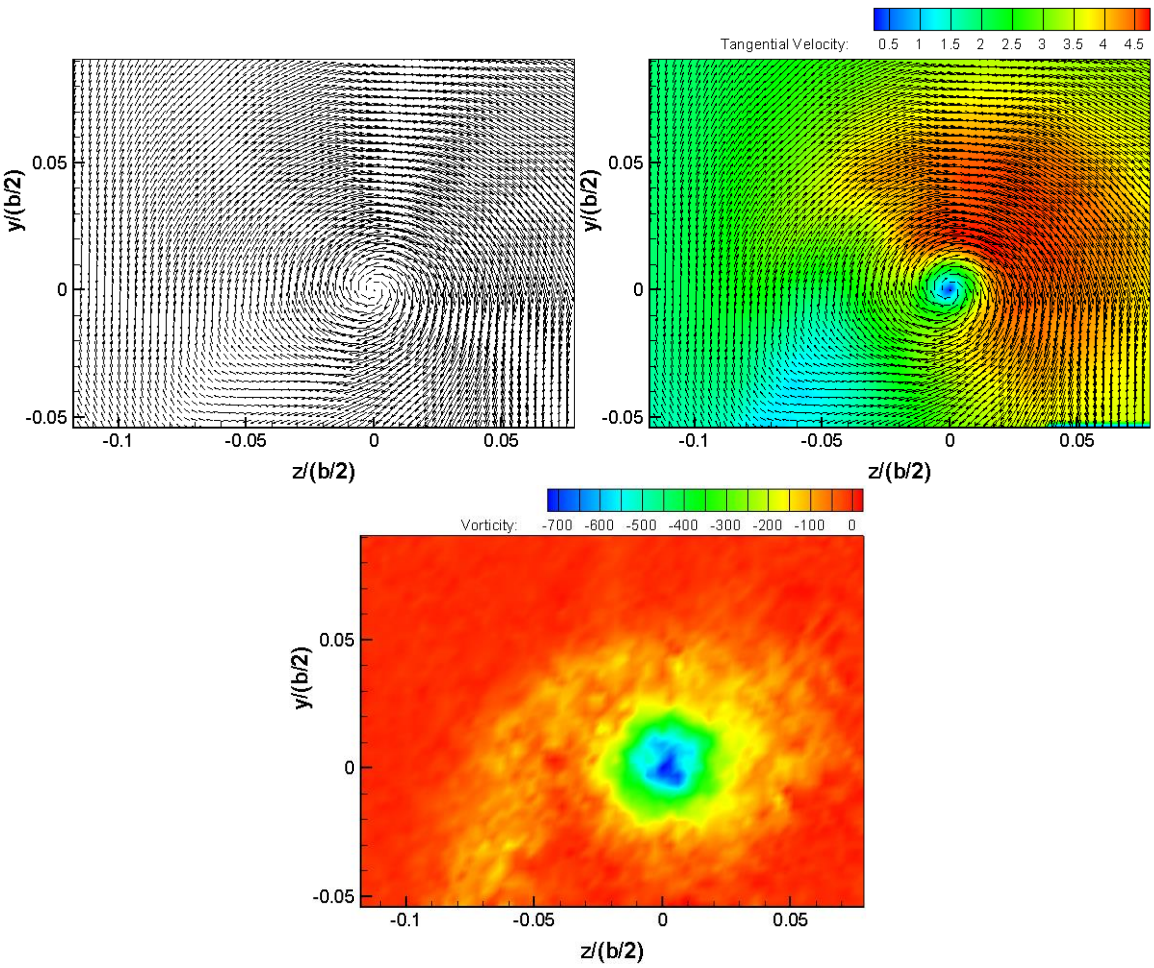


(a) HLC case, α = 7.7°, downstream location *x*/(b/2) = 0.548, V_∞ = 12 m/s



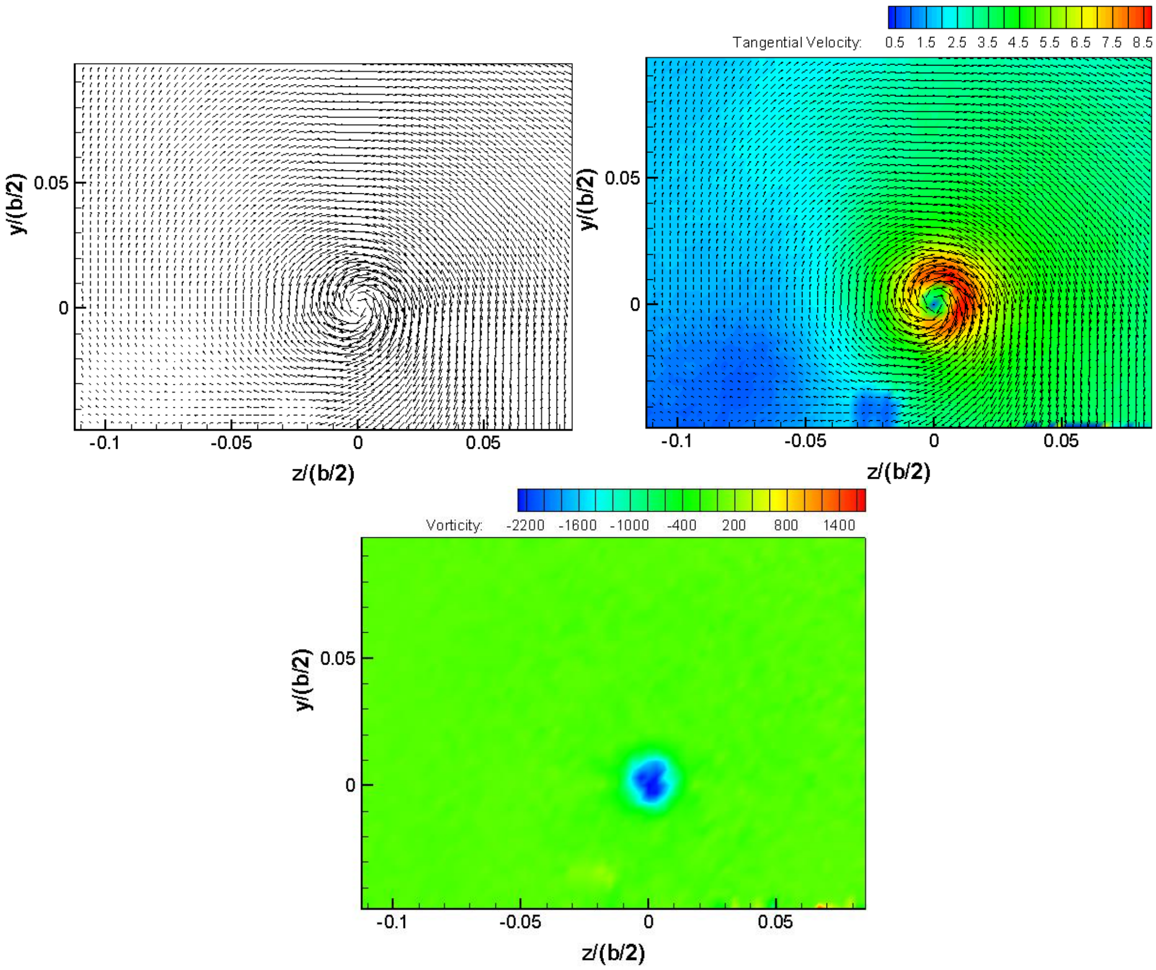


(b) HLC with S-rdw, α = 9.7°, $\varphi_{S\text{-}rdw}$ = -30°, downstream location x/(b/2) = 0.548, V_∞ = 12 m/s

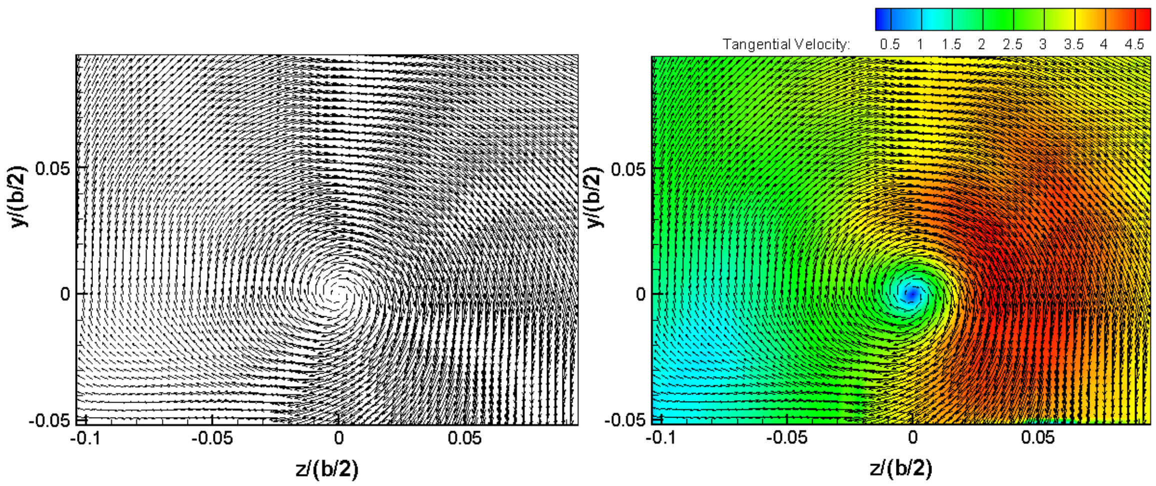


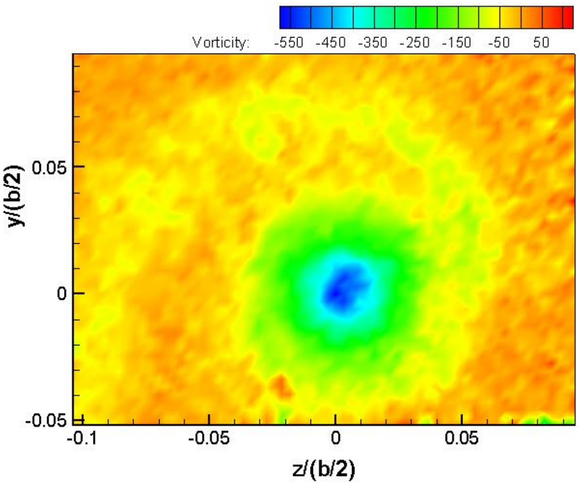
(c) HLC with L-rdw, α = 9.7°, $\varphi_{L\text{-}rdw}$ = -30°, downstream location x/(b/2) = 0.548, V_∞ = 12 m/s

Fig. 6. Velocity vectors, tangential velocity magnitude and vorticity magnitude at downstream location x/(b/2)=0.548

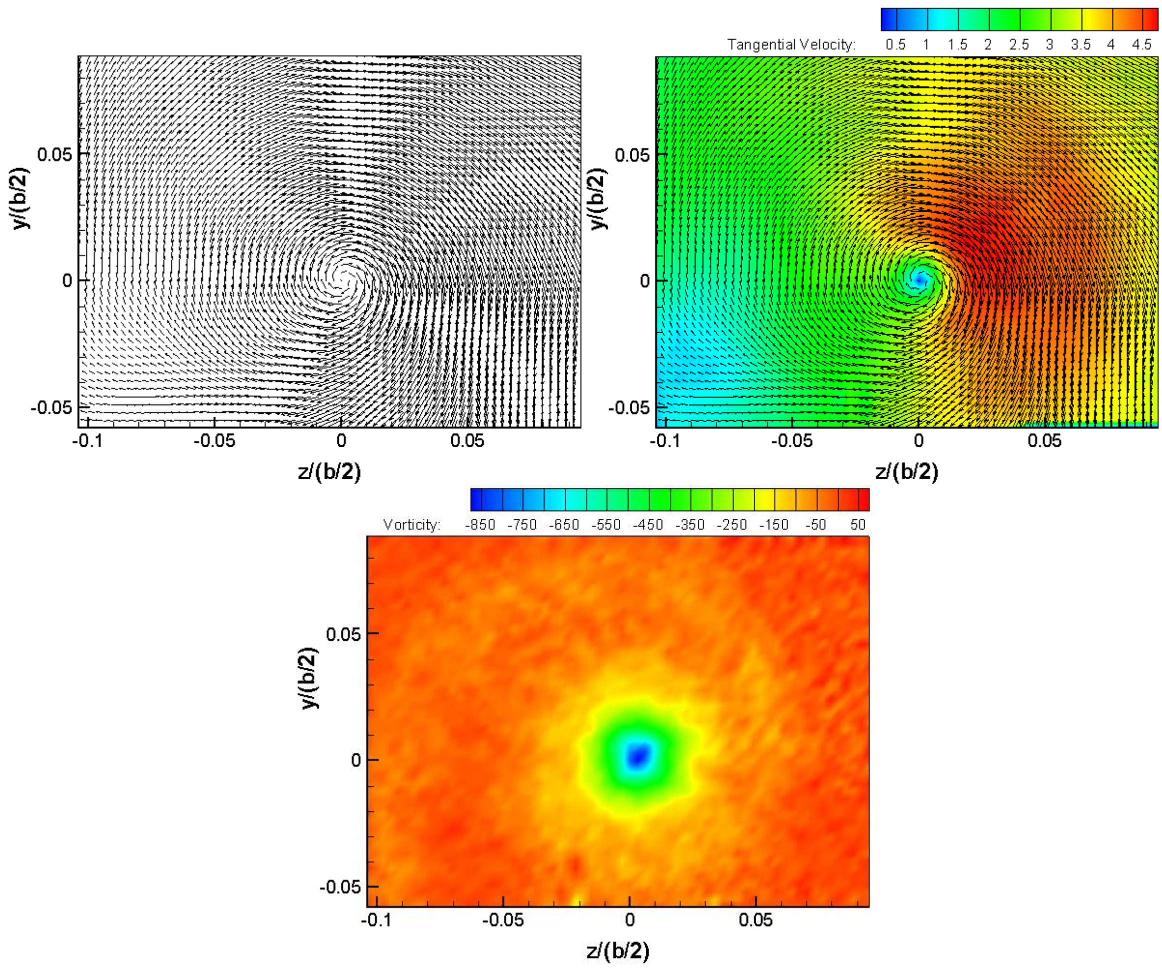


(a) HLC case, α = 7.7°, downstream location $x/(b/2)$ = 1.075, V_∞ = 12 m/s



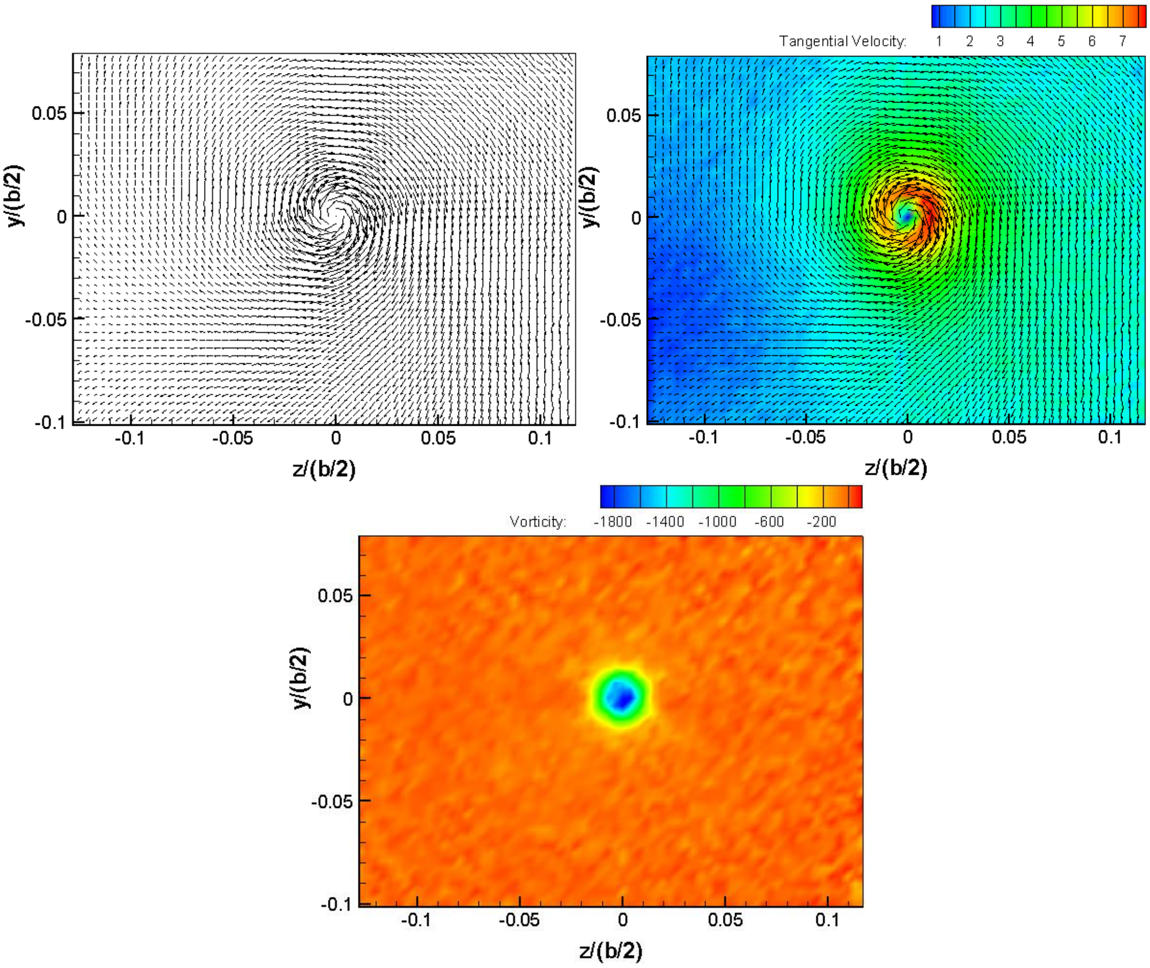


(b) HLC with S-rdw, α = 9.7°, $\phi_{S\text{-}rdw}$ = -30°, downstream location *x*/(b/2) = 1.075, V_∞ = 12 m/s

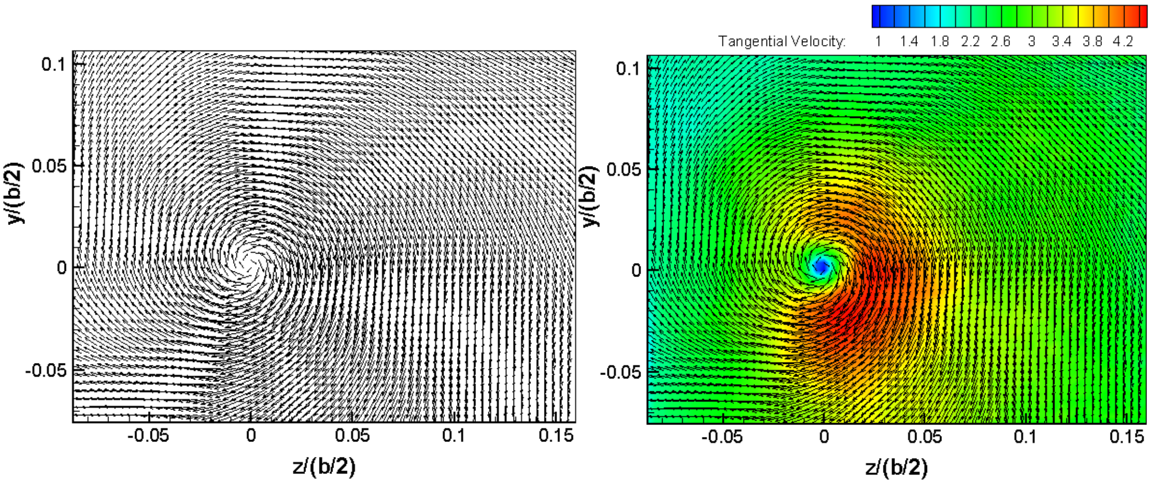


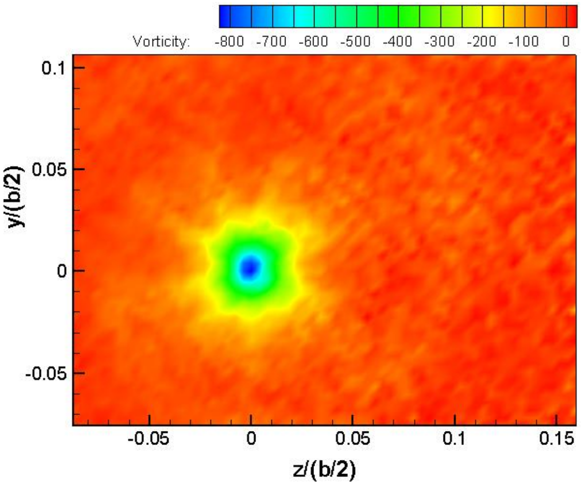
(b) HLC with L-rdw, α = 9.7°, $\phi_{L\text{-}rdw}$ = -30°, downstream location *x*/(b/2) = 1.075, V_∞ = 12 m/s

Fig. 7. Velocity vectors, tangential velocity magnitude and vorticity magnitude at downstream location *x*/(b/2)=1.075

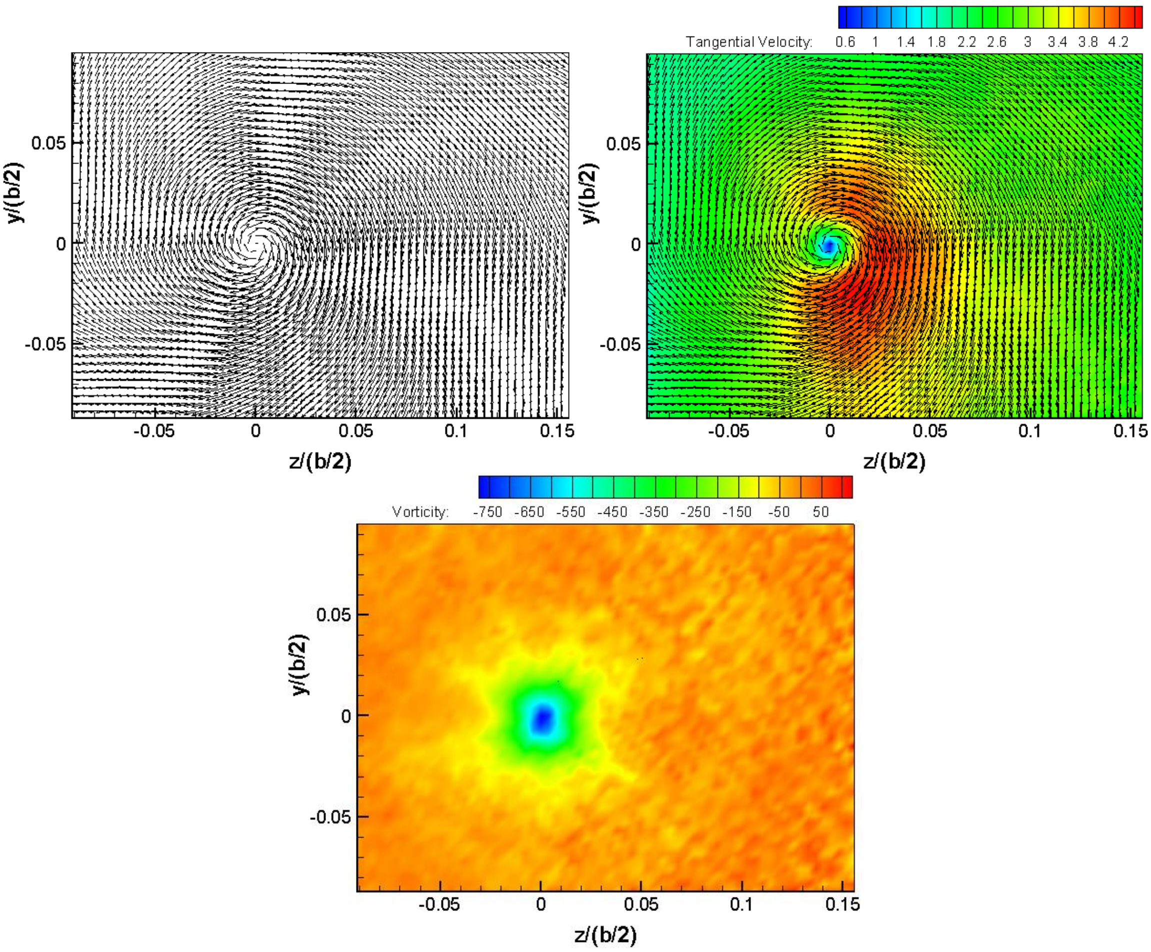


(a) HLC case, α = 7.7°, downstream location *x*/(b/2) = 2.387, V_∞ = 12 m/s





(b) HLC with S-rdw, α = 9.7°, $\phi_{S\text{-}rdw}$ = -30°, downstream location *x*/(b/2) = 2.387, V_∞ = 12 m/s



(c) HLC with L-rdw, α = 9.7°, $\varphi_{L\text{-}rdw}$ = -30°, downstream location *x*/(b/2) = 2.387, V_∞ = 12 m/s

Fig. 8. Velocity vectors, tangential velocity magnitude and vorticity magnitude at downstream location *x*/(b/2)=2.387

As shown in Figures 6b-c, 7b-c, and 8b-c, in the presence of a reverse delta type add-on device, the tangential velocity magnitude of the resultant vortex decreases significantly with respect to the HLC wing tip vortex. From downstream planes 2 to 4, the tangential velocity reduction for the HLC is 7.6% only, whereas the maximum tangential velocity reduction between HLC and HLC with add-on devices is 43.6% for the Small reverse delta type add-on device (S-rdw) and 44.1% for the Large reverse delta type add-on device (L-rdw). This large decrease in the tangential velocity magnitude is indicative of a weaker resultant vortex with a more rapid diffusion with respect to the HLC case.

In all instances, the vorticity is seen to decrease slowly from a maximum at the center to nearly zero in the outer vortex regions. The vortex cores in all Figures are distinguishable indicating no major breakdown of the vortex cores. The vorticity contours in Figures 6b-c to 8b-c show that the resultant vortex is compact and strong. There is plenty of shed vorticity (tiny spots of vorticity) from the vortex core, but the vortex core itself has not broken down yet. However, compared to the HLC case, the peak vorticity magnitudes of the add-on device cases are significantly lower. From downstream planes 2 to 4, the vorticity reduction for the HLC is 16.6% only, whereas the maximum vorticity reduction between the HLC and HLC with add-on device is 54.9% for the S-rdw and 59.4% for the L-rdw. This indicates that the resultant vortex will diffuse at a higher rate than the wing tip vortex.

The vortex core size difference can be seen in Figures 5 to 8. At $x/(b/2)$ =0.548, the size of the radius of the merged vortex core increases by 181% and 221% for the S-rdw and L-rdw, respectively when compared with the vortex produced by the HLC alone. The resultant vortex core radius at $x/(b/2)$ =1.075 increases by 247% and 302% for the S-rdw and L-rdw, respectively, while at $x/(b/2)$=2.387, the resultant vortex core radius increases by 250% and 305% for the S-rdw and L-rdw, respectively.

It can be concluded that by introducing instability via a reverse delta type add-on device at roll angles (at zero angle of attack) in the wing tip vortex flow field does not alleviate the wake vortex as much as a reverse delta type add-on device at angles of attack (at zero roll angle), as studied earlier [17, 18]. Table 1 compares the results of the present and previous studies.

Table 1
Comparison of results of the present and previous studies

Authors	Vortex core size	Tangential velocity	Vorticity
Present Study	+305%	-44.1%	-59.4%
Altaf *et al.,* [17]	+557%	-82.9%	-92.6%
Altaf *et al.,*[18]	+37%	-36.1%	-
A. Altaf [18]	+463%	-79.6%	-85.6%

'+' signifies increase
'-' signifies decrease

4. Conclusions

An add-on device at various roll angles was mounted on a half-span wing model (*b*) at high lift configuration. The flow fields downstream of the modified model were measured using Particle Image Velocimetry (PIV). The measurements show a large increase in the resultant vortex core radius and a significant reduction in the tangential velocity and vorticity magnitudes when the reverse delta type add-on devices were placed. The resultant vortex core radius has increased by 250% and 305% for the S-rdw and L-rdw devices, respectively; the reduction in the maximum tangential velocity is 43.6% and 44.1% for both the add-on devices, respectively; and the reduction in the maximum vorticity is 54.9% and 59.4% for the two add-on devices, respectively. The resultant vortex is significantly weakened by the reverse delta type add-on devices attached at various roll angles. The diffused resultant vortex strength is significantly mitigated, and the following aircrafts will remain safe from dangerous large strength wake vortices. However, the add-on devices at roll angles do not alleviate wake vortices as considerably as add-on devices at angles of attack.

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