Experimental Investigation of the Influence of a Reverse Delta Type Add-on Device on the Flap-tip Vortex of a Wing

A Altaf\textsuperscript{1}\textsuperscript{a}, T B Thong\textsuperscript{1}\textsuperscript{b}, A A Omar\textsuperscript{2}\textsuperscript{c}\textsuperscript{*} and W Asrar\textsuperscript{3}\textsuperscript{d}

\textsuperscript{1}School of Engineering and Computer Sciences, New York Institute of Technology, P.O. Box 5464, Abu Dhabi, United Arab Emirates
\textsuperscript{2}Mechanical Engineering Department, University of Tripoli, P.O. Box 81507, Tripoli, Libya
\textsuperscript{3}Mechanical Engineering Department, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia

Email: \textsuperscript{a}aafaq@nyit.edu, \textsuperscript{b}tan.boon.thong@monash.edu, \textsuperscript{c}aao@aerodept.edu.ly, \textsuperscript{d}waqar@iium.edu.my

Abstract
Particle Image Velocimetry was used in a low speed wind tunnel to investigate the effect of interactions of vortices produced by an outboard flap-tip of a half wing (NACA 23012 in landing configuration) and a slender reverse delta type add-on device, placed in the proximity of the outboard flap-tip, on the upper surface of the half wing. This work investigates the characteristics of the vortex interactions generated downstream in planes perpendicular to the free stream direction at a chord-based Reynolds number of $Re_c = 2.74 \times 10^5$. It was found that the add-on device significantly reduces the tangential velocity magnitude and enlarges the vortex core of the resultant vortex by up to 36.1% and 36.8%, respectively.

Nomenclature

\begin{itemize}
\item $b$ = wing span length (m)
\item $Re_c$ = Reynolds number based on chord length
\item $r$ = radius, m
\item $r_c$ = core radius, m
\item $V_\theta$ = tangential velocity, m/s
\item $V_\infty$ = free stream velocity, m/s
\item $x$ = stream-wise coordinate, m
\item $y$ = span-wise coordinate, m
\item $z$ = transverse coordinate, m
\item $\alpha$ = angle of attack, deg.
\end{itemize}

1. Introduction
The study and control of swirling vortex flows is vital towards developing ways to suppress vortices generated by commercial aircraft which leads to a reduction in the hazard posed to trailing aircraft \cite{1, 2}.

Vortices created by aircrafts are an inevitable consequence of the creation of lift. Vortices persist for many kilometers and wake-vortex encounters pose a grave hazard to trailing aircrafts that fly in
close proximity near the airport runway especially during takeoff and landing [3] because the wake vortex circulation is at a maximum. Wake vortex and turbulence generated by large aircraft are strong and can be unsafe to the following aircraft which can experience motion anywhere from sudden upwash to downwash to uncontrollable rolls to sudden loss of altitude, depending on the aircraft’s position and orientation with respect to the wake [4]. Incidents have been recorded during landing approaches, when wake turbulence has resulted in fatal accidents because of insufficient time and altitude for pilots to regain full control of their aircraft after being severely affected by the strong vortices.

Vortex wakes are very slow to dissipate naturally and therefore there is a need to find ways of increasing the dissipation rate. One of the most promising concepts of vortex dissipation enhancement involve modification of the wing by means of winglets or wing fences attached to the suction surface of the wing. These wing devices either create countergyrotor vorticity that subsequently diminishes the intensity of the rolled up vortex or cause the vortex core dimension to be increased, which also hastens vortex dissipation [5].

Some of the most promising concepts of vortex modification make use of multiple vortex pair systems [6, 7, 8]. The addition of a strong vortex pair counter-rotating to the basic tip vortices can lead to more diffused vortices whose strength is the sum of the co-rotating and counter-rotating vortices.

Researchers are optimistic about solving wake hazard passively in the near-wake field. Numerous experimental investigations have been conducted with devices of various shapes and sizes to alter the vortex rollup process and to create instability in the wake of the aircraft so that the resultant vortex is enlarged and more diffused. Tests have been conducted with a spoiler mounted on the wing tip [9], splines mounted downstream of the wing tip [10] spoilers of delta type plan-form deployed in the area of the outboard flap [11], a tip-mounted slender half delta wing [12] and a tip-mounted reverse half delta wing [13].

Recent investigations have pointed out that reverse delta type add-on devices may have the capability to be used in vortex alleviation [2, 11, 13, 14]. Reverse delta type add-on device vortices may excite some instability (countersign vorticity) into the wingtip and flap-tip vortices and modify the vortex roll up process [2]. The interaction of the vortices would then tend to create a weaker resultant vortex with a reduction in peak vorticity, maximum tangential velocity and core circulation. These may lead to a diffused resultant vortex which can enhance wake vortex decay and thus, lead to wake vortex alleviation. The timings between consecutive landings and take-offs, and the separation distances between aircrafts can be reduced significantly by the use of a reverse delta type add-on device. This will directly increase the airports aircraft handling capacity and increase its profitability.

The purpose of this paper is to investigate the influence of the interaction of the vortices of a reverse delta type add-on device and the outboard flap-tip vortex.

2. Experimental Setup
The experiment was carried out in the closed-loop low-speed wind tunnel at the International Islamic University Malaysia (IIUM). The wind tunnel test section dimensions are 2.30 m (width), 1.50 m (height) and 6.00 m (length). The wind tunnel has a turbulence intensity of less than 0.11%.

A half wing model (NACA 23012 in landing configuration; slat extension 15° and flap extension 20°), shown in Fig. 1, is used in this investigation along with a reverse delta type add-on device, shown in Fig. 2. A reverse delta type add-on device is bounded by a leading edge and by a pair of trailing edges extending from the ends of the leading edge towards a trailing apex point. The reverse delta type add-on device has a bevel angle of 20° and is attached to the half wing model by a 20 mm long movable joint.

The velocity components in planes perpendicular to the stream-wise direction at four locations in the downstream direction are investigated. The experimental setup is shown in Fig. 3. Multiple laser positions are chosen so as to differentiate between their flow characteristics in terms of roll up, tangential velocity, vorticity and circulation.

PIV measurements are taken only at the half model outboard flap-tip with/without the reverse delta
add-on device attached. The CCD camera is focused at the half model wingtip at all downstream planes.

The free stream velocity was set to 12 m/s corresponding to a $Re = 2.74 \times 10^5$. The flow was seeded by particles of a mean diameter of 1 μm. Important PIV data acquisition parameters such as time interval ($\Delta t = 60 \mu s$) and laser sheet thickness (2 mm) were fixed. A light sheet from a Nd:YAG laser system of wavelength 532 nm was used to illuminate the flow. A Flow Sense M2 8 bit CCD camera with Micro-Nikkor 60 mm camera lens was placed perpendicular to the laser sheet, downstream of the wing.

PIV data was recorded for the High Lift Configuration (HLC) at $\alpha = 7.7^\circ$ and HLC with a reverse delta type add-on device at $\alpha = 9.7^\circ$. At 12 m/s, the HLC at an angle of attack 7º yields a target lift coefficient $C_L = 1.06$. When an add-on device was attached to the half wing model at HLC, it was found that increasing the half wing model angle of attack by 1º- 2º recovers the target lift coefficient that was achieved at HLC without the add-on device. Hence, the half wing model with the add-on device is tested at $\alpha = 9.7^\circ$. The reverse delta type add-on device angle of attack was fixed at $\alpha = 30^\circ$.

Figure 1. Schematic of the Half-Span Wing model. Dimensions are in millimetres [mm].
Figure 2. Schematic of the reverse delta type add-on device. Dimensions are in millimetres [mm].

Figure 3. Schematic of the experimental setup.
3. Results and Discussions

3.1 Velocity Vectors and Vorticity Contours

Vortices are very slow to dissipate naturally and may take several miles to dissipate downstream of a large aircraft. Vortex dissipation rate can be accelerated if the vortex core dimension is increased significantly by using vortex modification techniques such as using wing devices that can alter the vortex rollup process. A more diffused vortex core at the same downstream location implies a weaker vortex.

Figs. 4a-4h show the velocity vectors of a half wing model at HLC with/without a reverse delta type add-on device attached at a location near the half model outboard flap-tip. The results are obtained at four downstream planes; x/(b/2)= 0.021, 0.548, 1.075 and 2.387. This investigation was carried out to discover if the resultant vortex formed after the merging of the reverse delta type add-on device vortices and the flap-tip vortex yields a more diffused vortex.

a) High Lift Configuration case, $\alpha=7.7^\circ$, x/(b/2)=0.021, $V_\infty=12$ m/s.

b) High Lift Configuration case with reverse delta type add-on device, $\alpha=9.7^\circ$; x/(b/2)=0.021, $V_\infty=12$ m/s.
c) High Lift Configuration case, $\alpha=7.7^\circ$, $x/(b/2)=0.548$, $V_\infty=12$ m/s.

d) High Lift Configuration case with reverse delta type add-on device, $\alpha=9.7^\circ$; $x/(b/2)=0.548$, $V_\infty=12$ m/s.

e) High Lift Configuration case, $\alpha=7.7^\circ$, $x/c=1.075$, $V_\infty=12$ m/s.
f) High Lift Configuration case with reverse delta type add-on device, $\alpha=9.7^\circ$; $x/(b/2)=1.075$, $V_\infty=12$ m/s.

g) High Lift Configuration case, $\alpha=7.7^\circ$, $x/c=2.387$, $V_\infty=12$ m/s.

h) High Lift Configuration case with reverse delta type add-on device, $\alpha=9.7^\circ$; $x/(b/2)=2.387$, $V_\infty=12$ m/s.

**Figure 4.** Tangential Velocity Magnitude and Vorticity Contours for High Lift Configuration $\alpha=7.7^\circ$ and High Lift Configuration $\alpha=9.7^\circ$ with reverse delta type add-on device at $x/(b/2)=0.021$, 0.548, 1.075 and 2.387.
Figs. 4a, 4c, 4e and 4g show the velocity vectors, tangential velocity magnitude and vorticity contours of the HLC flap-tip vortex. It is observable that the flap-tip vortex is not very strong. This is because the flap deflection is set to $\delta=20^\circ$ only. A flap deflection of $\delta=20^\circ$ will yield a weaker vortex than a flap deflection of $\delta=40^\circ$ as less pressure differential exists. It is clearly noticeable that the flap-tip vortex is well rolled up at downstream plane $x/(b/2)=0.548$ but the vortex rollup is weaker (less compact vortex) at a farther downstream plane. The tangential velocity magnitude is seen to decrease slightly between downstream planes. Reynolds [15] attributed the reduction in the tangential velocity to the growth of the vortex in order to conserve momentum. As the vortex propagates through the fluid its volume increases with time due to the entrainment of the surrounding fluid.

The flap-tip vortex of the HLC without the add-on device exhibits a better rollup than the HLC with the add-on device, as shown in Figs. 4c, 4e and 4g. The flap-tip vortex of the HLC has diffused (enlarged) from $x/(b/2)=0.548$ to $x/(b/2)=1.075$ by 12.1% and from $x/(b/2)=1.075$ to $x/(b/2)=2.387$ by 20.8%. This increase in vortex core radius within 2 half-span lengths is significantly high. This indicates that the flap-tip vortex of the HLC is not very strong and hence, it has significantly diffused without any instabilities being introduced. When the reverse delta type add-on device is used, as shown in Figs. 4b, 4d, 4f and 4h, the vortex core radius is found to have diffused more than the HLC case. At $x/(b/2)=0.548$, the resultant vortex core radius compared to the flap-tip vortex core radius of the HLC has increased by 31.9% for the reverse delta type add-on device case. At $x/(b/2)=1.075$, the resultant vortex core radius compared to the flap-tip vortex core radius of the HLC has increased by 36.8% for the reverse delta type add-on device case. At $x/(b/2)=2.387$, the resultant vortex core radius compared to the flap-tip vortex core radius of the HLC has increased by 33.4% for the reverse delta type add-on device case. The significant increase in resultant vortex core radius indicates that the reverse delta type add-on device is capable of alleviating wake vortex strength.

When a reverse delta type add-on device is used the tangential velocity magnitude of the resultant vortex is seen to decrease slightly with respect to the HLC flap-tip vortex. It can be said that the add-on device reduces the tangential velocity magnitude of the resultant vortex which enables the resultant vortex to diffuse (weaken and enlarge) more rapidly than the HLC case.

For all investigated cases, the vorticity decreased gradually from a maximum at the centre to nearly zero at the outer region of the vortices. At $x/(b/2)=0.021$, closer vorticity contours at the centre of the vortex are recorded, as shown in Figs. 4a-b. It can be noticed that the vortex cores are distinguishable. At $x/(b/2)=0.548$, the vortex core for the HLC only is distinguishable (Fig. 4c), whereas the vorticity contours for the add-on device case (Figs. 4d, 4f and 4h) are broken into small vorticity patches. These small patches of vorticity have high individual vorticity magnitudes but they do not pose a hazard as they are too tiny to cause any significant circulation of the entire vortex core. At farther downstream locations, the tiny vorticity patches increase in number for the add-on device cases. This suggests that the vortex core is mostly diffused/scattered/distributed and hazard from such vortices is minimal. A rapidly diffusing vortex rejects vorticity from the vortex core. The rejection of vorticity reduces the circulation of the vortex and its strength [16]. For the HLC, the vortex core is only largely diffused at $x/(b/2)=2.387$. Thus, it can be said that when the add-on device is used, the resultant vortex formed diffuses earlier and more rapidly than the HLC case.

The direct interaction of the vortices generated by the add-on device with the flap-tip vortex creates a resultant vortex with a weaker rollup, lower tangential velocity and larger vortex core. The vortex system with co-rotating and counter-rotating vortices experiences a lower tangential velocity due to instabilities created by the direct interaction of the co-rotating and counter-rotating vortices within the vortex system which lead to an enlarged and weaker resultant vortex [2]. The flap-tip vortex and the reverse delta type add-on device vortex in close proximity of the flap-tip are co-rotating vortices, as shown in Fig. 4b. These co-rotating vortices are very close to each other and at the point where the vortices meet; they have opposite direction of rotation. There is also a counter rotating vortex of the reverse delta type add-on device present. The interaction between these three vortices lowers the
tangential velocity of the resultant (merged) vortex and causes it to diffuse rapidly, as shown in Figs. 4a-4h. It can be concluded that the use of a reverse delta type add-on device causes the resultant vortex to diffuse rapidly.

3.2 Tangential Velocity

Figure 5. Non-dimensional tangential velocity distributions of HLC, and HLC with L-rdw at (a) x/(b/2)=0.548, (b) x/(b/2)=1.075 and (c) x/(b/2)=2.387.

The tangential velocity around the vortex centerline, $V_\theta$, is calculated as
$$v_\theta(r) = \frac{1}{k} \sum_{i=1}^{k} v_{\theta,i}(y,z) \bigg|_{r=\sqrt{y^2+z^2}}$$
where $k$ is the number of points for each radius; $r = \sqrt{y^2+z^2}$; $V_\theta$ is normalized by the free stream velocity $V_\infty$ and plotted versus the radial distance from the vortex centerline $r$, normalized by the half span (b/2); and $r_c$ is defined as the core radius of the tip vortex, where maximum tangential velocity occurs [17].
From Figs. 5a-c, the reduction of tangential velocity at the vortex core for the HLC from \( x/(b/2)=0.548 \) to \( x/(b/2)=2.387 \) is 19.6%. Whereas, the tangential velocity reduction of the resultant vortex core from \( x/(b/2)=0.548 \) to \( x/(b/2)=2.387 \) for the reverse delta type add-on case is 36.1%. There is a 16.5% higher reduction in tangential velocity magnitude when the reverse delta type add-on device is used. This significant reduction in tangential velocity magnitude causes the vortex to diffuse more rapidly and hence, alleviate wake vortex strength.

From Figs. 5a-c, it is evident that the resultant vortex core radius has increased significantly when the reverse delta type add-on devices are used.

4. Conclusion
Reverse delta type add-on device was attached to a half wing model in the proximity of the outboard flap-tip at HLC and its resultant downstream vortex structures were obtained using Particle Image Velocimetry (PIV) in the IIUM closed-loop low-speed wind tunnel.

The vortex structures showed that there was a significant increase in the resultant vortex core radius and a significant reduction in the tangential velocity magnitude of the resultant vortex compared to the flap-tip vortex core radius at HLC.

The maximum tangential velocity reduction recorded between downstream plane 2 and downstream plane 4 for the HLC was 19.6% whereas the maximum tangential velocity reduction for the reverse delta type add-on device case was 36.1%

The reverse delta type add-on device case is more favourable as its tangential velocity magnitude is lower and the resultant vortex is more diffused (weaker and larger vortex core radius) than the HLC case.

From the above observations, it can clearly be seen that the reverse delta type add-on device has several benefits. The add-on device results in a significant reduction in tangential velocity magnitude and a significant increase in the resultant vortex core radius which ensures that the vortex strength is significantly weakened. The weak resultant vortex will continue to decay rapidly and this will avoid trailing aircrafts to encounter strong swirling vortical flows. This permits aircraft spacing to be reduced, time between consecutive landings and take-offs to be reduced and aircraft capacity at airports to be increased.

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