Flow Visualization of Vortex Lift on Highly Swept Tailless Delta Wing

Brandon Lim

Carson Brashear

Alex Tschinkel

Sikuang Wang

Summary

Experimental Setup, Materials, Instrumentation and Facilities

The experimental investigation of vortex lift was performed on the Lockheed Martin Innovative Control Effectors design. This is a highly swept delta wing with a sweep angle of 65 degrees, no vertical stabilizer, and a stall angle of 35 degrees. This design was chosen for the experiment because vortex lift plays a major role in the aerodynamics as well as current research interests such as lateral instability due to vortices. A scaled FDM 3D-printed model was used for the flow visualization.

To visualize the vortex lift, a particle imaging velocity laser system and wind tunnel were used. The University of Utah has a subsonic boundary layer wind tunnel that can achieve flow speeds from 5 - 45 m/s. The model was kept out of the boundary layer for this experiment in the unperturbed flow region. By seeding the air in the wind tunnel with a particle seeder, olive oil droplets were diffused into the free stream to create reflective references for a top-mounted PIV laser to reflect off of. By adjusting the laser intensity to a visual, but non-harmful wavelength, the flow could be visualized within the reference plane of the laser. Figure 1.1 shows the experimental setup schematic. As seen from the figure, the PIV laser is mounted on the top of the wind tunnel and illuminates a laser plane in the lateral direction of the delta wing. This lateral plane visualization shows the vortex tube roll up the best.

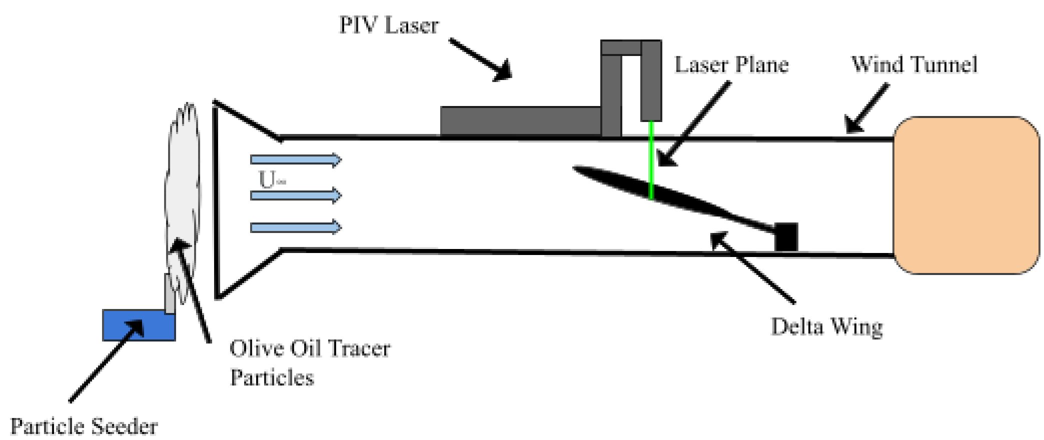

Figure 1.1: Experimental Setup Schematic

Figure 1.2 below shows the actual experimental setup with the delta wing mounted on a sting and the laser system can be seen above the test section. For video capture, the tracer particles and PIV laser created a sufficient flow visualization for normal phone cameras to capture. No extra camera adjustments or equipment were required to obtain adequate flow visualization. Although, in post processing, some lighting adjustments were made to further distinguish the vorticity behavior from unperturbed tracer particles. This can be seen in Figure 1.3 where exposure and contrast were adjusted to create a sharper images of flow visualization.

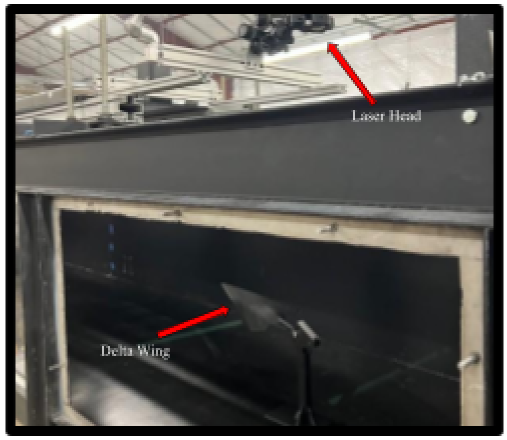

Figure 1.2: Experimental Setup

Case Studies and Relevant Parameters

A major non-dimensional parameter in the study of aerodynamics is the Reynolds number where the characteristic length scale used is the wing chord length. For delta wings that have non-uniform chord lengths, the mean aerodynamic chord length is used. In this experiment, the Reynolds number was the main parameter that varied between case studies. The first case study had a Reynolds number of 100496 which was chosen as a common Reynolds number for subsonic speed study in academic research of this aircraft. This Reynolds number was achieved from having a relatively higher velocity of 8 m/s. The second case study had a Reynolds number of 62810 which was chosen to visualize the potential changes in vorticity at slower flight speeds than what is commonly investigated. This corresponded to a slower velocity of 5m/s. Further, 3 angles of attack were chosen to be visualized for each case study's Reynolds number. These 3 angles of attack were 20°, 30°, and 40° which represent an operational angle of attack, pre-stall angle of attack, and post-stall angle of attack respectively. By varying angle of attack with Reynolds number, the coefficient of lift and drag are consequently being varied between case studies as well. Figure 1.3 below shows the vortex structure for higher and lower Reynolds numbers at 40 degrees angle of attack.

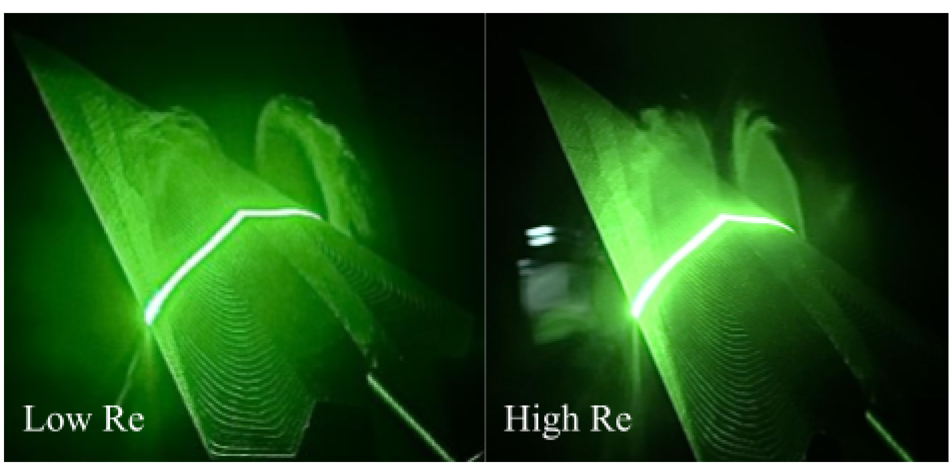

Figure 1.3: Vortex Tube Flow Visualization for Low Reynolds Number (left) and High Reynolds Number (right) at an Angle of Attack of 40°

Discussion of Vortex Lift on Highly Swept and Tailless Delta Wings

Delta wing aircraft with sweep angles greater than 55 degrees are classified as highly swept or slender delta wings and are exceedingly susceptible to the generation of leading edge vortices. These vortices form due to flow separation at the leading edge which roll up into vortex tubes and travel down the length of the body. Vortex tube formation has been studied extensively within the aerodynamics community and can be primarily attributed to two phenomena.

The first phenomena is through a pressure difference where higher pressure flow on the bottom of the aircraft wraps the separated leading edge flow around to lower pressure regions on the top of the aircraft which propagate into vortex tubes. This is the same flow physics that describes why wingtip vortices form on traditional aircraft wings. The only difference is that these vortices propagate into vortex tubes and attach back to the aircraft. The second phenomena of vortex tube formation involve shear layer interactions after leading edge separation. The shear layer is a region in separation between the wake and the primary flow where fast moving fluid and slow moving fluid interact to generate vorticity. Through Kelvin-Helmholtz instability of the shear layer, increased growth in fluid vorticity rolls the shear layer up into a primary vortex core which is the vortex tube.

When these vortex tubes form, they are symmetric about the midline of the delta wing and the vortex structure reattaches to the upper surface. This can be seen in Figure 2.1 below. The high energy vortex tubes have relatively fast moving air and create a low pressure region and therefore suction. This ultimately leads to a phenomenon known as vortex lift.

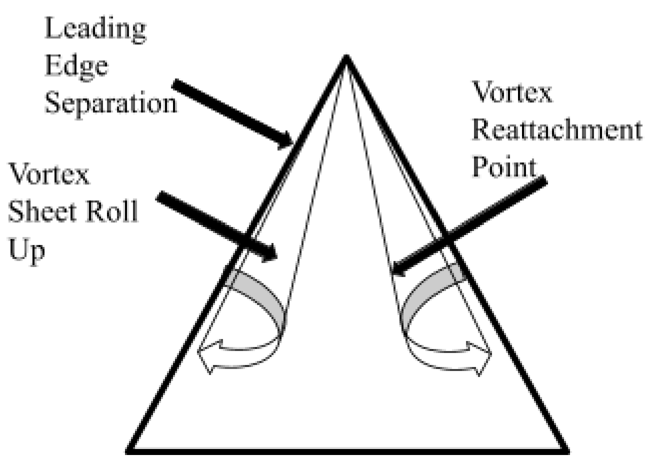

Figure 2.1: Vortex Tube Formation

Vortex lift, in comparison to traditional lift, increases the angle of attack envelope of aircraft which is desirable in UAV or military applications where high maneuverability and increased aerodynamic performance is a priority. For comparison, traditional NACA airfoils do not generate vortex lift on their own and stall around 15 degrees angle of attack. The highly swept delta wing used in the flow visualization experiment, Lockheed Martin Innovative Control Effectors design, stalls around 35 degrees angle of attack. Although its geometry is constructed from 3 traditional airfoils that resemble NACA airfoils, the high sweep angle and planform geometry generate vortex lift which accounts for the delayed stall.

Wind tunnel data on aircraft that generate vortex lift show a non-linear rise in lift coefficient with angle of attack which differs from the linear behavior of traditional airfoil lift. This is due to an increased strength of vorticity with higher angles of attack which has a non-linear relationship. Attempts at quantifying and predicting lift for delta wings have followed a similar methodology of first predicting body normal force due to the effects of vortex interaction. Aircraft Performance and Design by John D. Anderson approximates this normal force as

$$\frac{C_N}{(s/l)^2} = 2\pi\left(\frac{\alpha}{s/l}\right) + 4.9\left(\frac{\alpha}{s/l}\right)^{1.7}$$

where l is the length of the delta wing, s is the semispan, and α is the angle of attack. As seen from this equation, the normal force coefficient is non-linearly dependent on the angle of attack which aligns with experimental data seen in research. From here, the coefficient of lift can be calculated as

$$C_L = C_N cos\boldsymbol{\alpha}$$

Although increased angle of attack envelopes and greater maneuverability is a favorable consequence of vortex tube formation, the fluid phenomena is not without consequences. Inherit vortex instabilities and slight perturbations in pressure result in a multitude of vortex behaviors that are undesirable in flight. Vortex breakdown on the body of the aircraft is typically asymmetric between the port and starboard sides. Especially at higher angles of attack or different roll angles, the vortex tubes will break down asynchronously or non-symmetrically. These slight differences in vortex breakdown cause instantaneous differences in lift between port and starboard sides which lead to an unsteady roll moment in flight. Kelvin-Helmholtz instability and turbulent wakes can also lead to vortex tube lateral wandering over the top of the wing. Again, this is typically an asymmetric phenomena which contributes to pressure and lift differentials leading to unsteady roll moments. Research has shown that the unsteady roll moment has a frequency that corresponds to a Strouhal number of 1 with a characteristic length of wing span. The strouhal number is given by the equation

$$St = \frac{fL}{U}$$

where f is the frequency of the unsteady rollment, L is the characteristic length, and U is the freestream velocity.

For the Lockheed Martin ICE design used in this flow visualization, the tailless aspect of the delta wing has an exacerbation in these unsteady aerodynamics. The absence of a vertical stabilizer and relatively small wing span due to a high sweep angle reduce the aircraft's damping of differences in port and starboard lift. As a result, perturbations in port and starboard lift create a rocking in the aircraft's roll moment. This is currently a research topic within aerodynamics where interventions such as active flow control are being explored for stability.

In summary, leading edge vortices form on highly swept delta wings and propagate into vortex tubes on the suction side of the aircraft. These vortex tubes are sources of low pressure which enhance the lift capabilities of delta wings. Vortex lift increases aerodynamic performance but also results in unfavorable stability characteristics such as unsteady roll moments due to vortex breakdown. Overall, aircraft can take advantage of these flow phenomena to gain an upper hand in maneuverability and performance if the instability is accounted for.

References

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