Analysis of Leading-Edge Droop Flaps on Aerodynamic Lift at Different Angles of Attack

Purpose

This project aims to quantify the impact of leading-edge droop flaps on aircrafts' aerodynamic lift at low-speed and high angle of attack operations.

Abstract

High-lift devices on aircraft are critical to the safety of flight operations, particularly during takeoffs and landings where the aircraft must generate sufficient lift to overcome its weight. The purpose of this study is to compare the effects of leading-edge droop flaps on aerodynamic lift at high and low angles of attack (AoA). Using the POWERUP 4.0 remote-controlled paper airplane, data was collected from three plane models in four categories each – clean configuration at 0° AoA, at 15° AoA, and dirty configuration (droop flaps extended) at 0° AoA and 15° AoA. In each category, 10 trials were conducted to measure the airborne time after the throttle was reduced from 35% to 7%. After 40 trials with the Invader model, it saw an average increase of 3.498 seconds at 15° AoA with droop flaps, a 116.8% increase compared to without droop flaps. At 0° AoA, the mean difference was 1.738 seconds, a 66.8% increase. At 15° AoA, the Onslaught with droop flaps flew for 1.132 seconds longer on average, a 34.8% increase. However, because the p-values for Onslaught (0° AoA) and Valkyrie are over 0.05, conclusions could not be made from those data. These findings indicate that leading-edge droop flaps increase the airborne time more at higher AoAs, when comparing the same model. Although never implemented, leading-edge devices could have increased the Concorde's operating range since they produce extra lift at subsonic cruise segments and decrease fuel burn, which are crucial for increasing the efficiency of future supersonic aircraft.

Hypothesis

If two airplanes – one in clean configuration and one with droop flaps extended – fly at a high angle of attack while descending, the aircraft with droop flaps extended will stay airborne for longer. However, when flying at a low angle of attack, the aircraft with droop flaps will inversely affect its airborne time.

Introduction

On August 20, 2008, Spanair Flight 5022 lifted off from El Prat Airport with 172 occupants and began its journey to Gran Canaria. Seconds later, the aircraft rolled sharply to the right, and was engulfed in flames before the flight crew could correct the bank angle. On August 31, 1988, Delta Flight 1141 lifted off from DFW Airport with 108 souls on board. Within ten seconds, it struck an ILS Localizer antenna and partially disintegrated midair, bursting into flames on ground impact after being airborne for only 22 seconds. Many similar aviation accidents follow along with these descriptions, where the aircraft struggled to achieve a positive climb rate after takeoff. These two investigation reports found that the pilots misconfigured the flaps and slats before takeoff, which did not create enough difference in air pressure above and below the wings to lift the plane off the ground. Essentially, the aircraft had insufficient lift to overcome its weight.

High-lift devices, specifically the trailing-edge flaps and leading-edge slats, increase the wing camber to help produce more lift at low-speed operations, such as takeoffs and landings where the aircraft's angle of attack (AoA) is higher than usual. Although flaps and slats are usually simultaneously extended to maximize the amount of lift created, this study specifically focuses on the leading-edge droop flaps, which are used on commercial aircraft such as the Airbus A350 and A380. Unlike the slats, which are designed to move away from the wing's leading-edge and create a gap when they are extended, droop flaps rotate directly downward to increase the camber size. This experiment seeks to determine the percent increase of lift with leading-edge droop flaps extended at high and low angles of attack.


a


b


c


d

Figures 1a-d (above). From left to right, the Invader model in clean configuration, The Invader model with droop flaps, the Onslaught model in clean configuration, and the Valkyrie model with droop flaps.

Lift is usually quantified by the lift coefficient, which is dependent on the lift force, velocity, wing area, and atmospheric density. To evaluate aircraft performance at low-speed operations, this study used the POWERUP 4.0 Smartphone Controlled Paper Airplane and measured the number of seconds that the aircraft remained airborne after its throttle was reduced from its cruising altitude. The time was stopped as soon as the plane landed. Data were collected on four categories – no droop flaps at 0° AoA, no droop flaps at 15° AoA, droop flaps at 0° AoA, and droop flaps at 15° AoA. Ten trials were conducted in each category, and three paper plane models were used to test the consistency of the results – the Invader, Onslaught, and Valkyrie models.

Procedures

Constructing Airplane Models

- Prepare 6 sheets of paper provided by the POWERUP 4.0 Smartphone-controlled Paper Airplane Kit. Follow the folding instructions and construct 2 Invader models, 2 Onslaught models, and 2 Valkyrie models.
- Design the leading-edge droop flaps on only one of each model. Make two cuts – one near the pointed nose and one near the wingtips. The depth of each cut should be 0.7cm and perpendicular to the leading-edges.
- Once the cuts are completed, pinch the droop flaps and tilt them 45 degrees downward. Make them as circular as possible.

Takeoffs & Landings
(Invader, clean configuration)

- Calibrate the elevators using the POWERUP trim card.
- Hold the paper plane horizontally and gradually increase the throttle on the phone to 60%. Launch the plane into the wind and slightly adjust the throttle for a successful takeoff.
- After 5 seconds, reduce the throttle to 35% as the cruising throttle.
- Abruptly reduce the throttle to 7%. Immediately start the stopwatch and stop when the aircraft touches the ground. Record the elapsed time.
- Repeat the process above, but this time slide the angle of attack to 15 in the tuning menu.
- Alternate between 0° AoA and 15° AoA to get ten trials for each angle of attack setting.

The same process should be repeated using the same model but with droop flaps. The other two plane models also follow the same process.

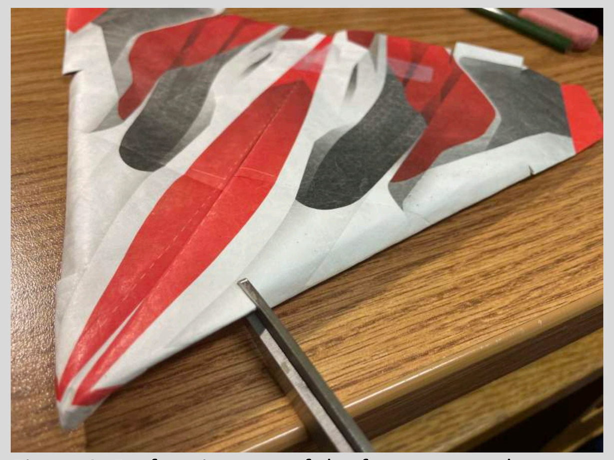
Figure 2. Performing one of the four cuts on the leading-edges.


Figure 4. The Valkyrie model in action. Out of the three models, the Valkyrie has the largest wing area but the lowest aspect ratio.

Figure 3. From left to right, setting throttle at 60% for takeoff, reducing the throttle to 35% for cruising, and abruptly reducing the throttle to 7% for a powered descent.

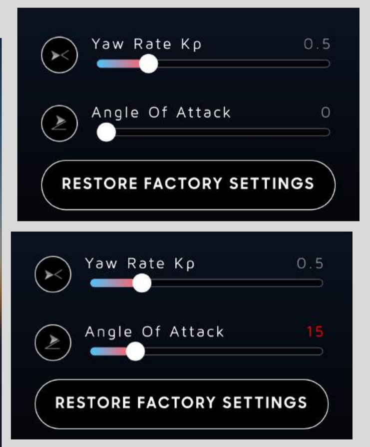

Figure 5. From top to bottom, setting the AoA to 0 degree and 15 degrees in the tuning menu. These two settings are alternated to reduce the impact of of the confounding variable – the wind.

Results & Analysis

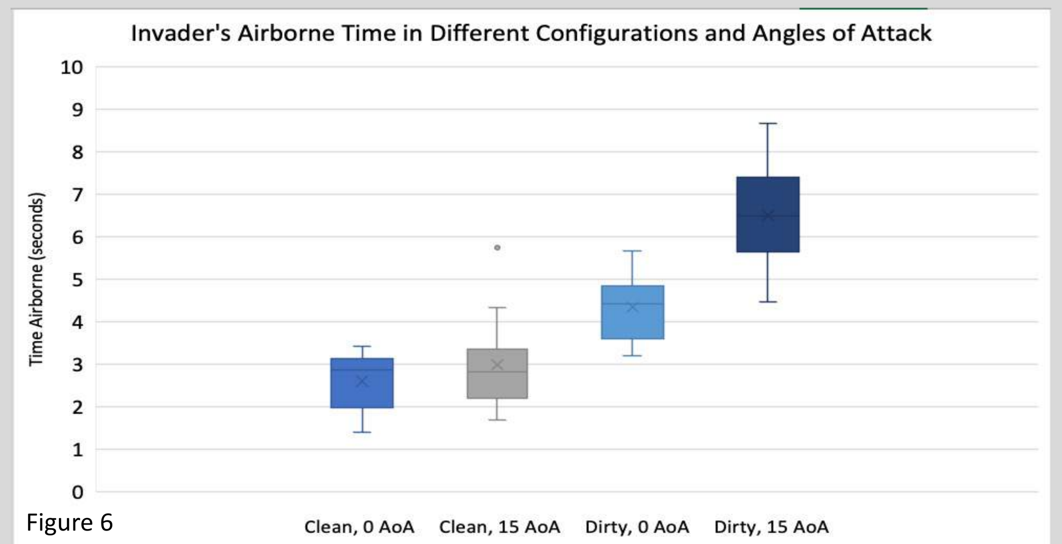

Figure 6

	Clean (0 AoA)	Clean (15 AoA)	Dirty (0 AoA)	Dirty (15 AoA)
	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)
Trial 1	3.08	2.26	4.03	6.72
Trial 2	3.26	5.75	4.63	7.18
Trial 3	1.41	3.02	4.23	5.93
Trial 4	2.69	2.29	4.69	6.24
Trial 5	1.83	2.9	4.71	8.66
Trial 6	2.02	1.69	5.66	6.78
Trial 7	2.16	2.05	5.24	8.11
Trial 8	3.42	2.87	3.71	6.05
Trial 9	3.05	2.78	3.2	4.78
Trial 10	3.08	4.33	3.28	4.47
Mean	2.6	2.994	4.338	6.492
Std. Dev.	0.692692011	1.20540634	0.804443217	1.313204731

Table 1. Data collected using the Invader model. The mean difference between Clean (0° AoA) and Dirty (0 AoA) was 1.738 seconds, a 66.8% increase. The mean difference between between Clean (15° AoA) and Dirty (15 AoA) was 3.498 seconds, a 116.8% increase.

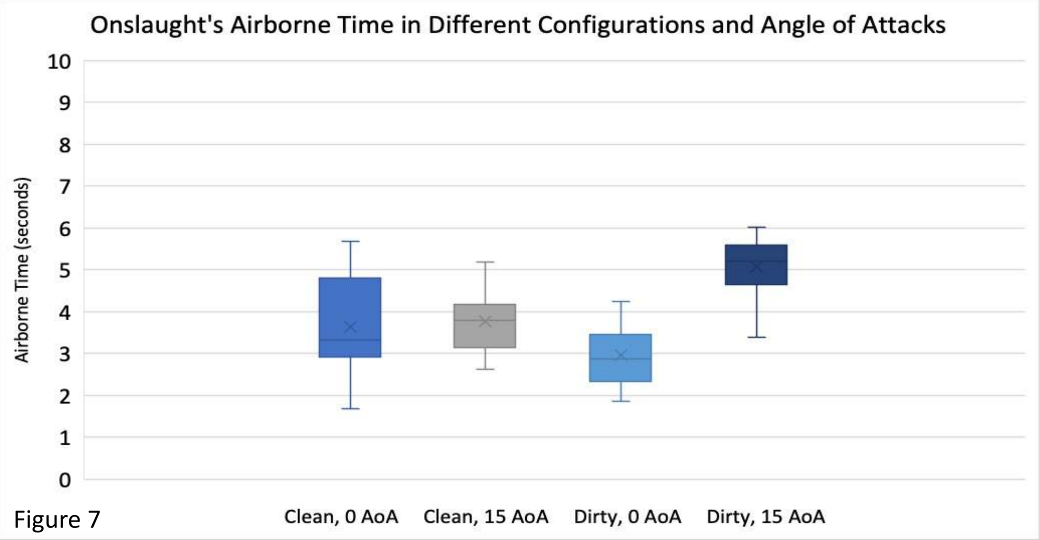

Figure 7

	Clean (0 AoA)	Clean (15 AoA)	Dirty (0 AoA)	Dirty (15 AoA)
	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)
Trial 1	4.71	4.29	4.23	4.54
Trial 2	3.36	5.18	2.87	6.02
Trial 3	5.69	3.84	2.36	3.38
Trial 4	5.11	3.75	3.02	5.42
Trial 5	3.29	4.03	1.85	5.8
Trial 6	3.05	4.13	4.13	4.68
Trial 7	2.48	3.08	2.69	5.26
Trial 8	1.68	3.17	2.86	5.14
Trial 9	3.12	3.57	2.27	5.02
Trial 10	3.78	2.63	3.23	5.53
Mean	3.627	3.767	2.951	5.079
Std. Dev.	1.22623226	0.717759632	0.761335814	0.75286785

Table 2. Data collected using the Onslaught model. The mean difference between Clean (0° AoA) and Dirty (0 AoA) was –0.676 seconds, a 18.6% decrease. The mean difference between between Clean (15° AoA) and Dirty (15 AoA) was 1.132 seconds, a 34.8% increase.

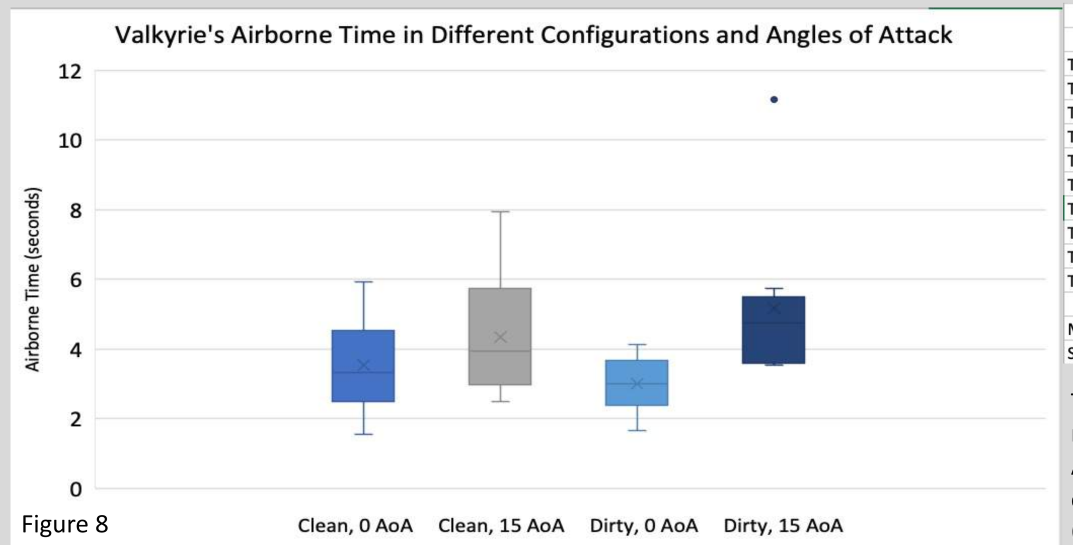

Figure 8

	Clean (0 AoA)	Clean (15 AoA)	Dirty (0 AoA)	Dirty (15 AoA)
	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)	Time Airborne (s)
Trial 1	3.84	7.93	2.23	4.46
Trial 2	3.23	6.05	1.66	3.54
Trial 3	5.38	4.51	3.2	3.54
Trial 4	5.93	4.75	2.42	5.74
Trial 5	4.26	5.63	3.47	4.26
Trial 6	2.53	3.35	3.63	5.01
Trial 7	3.39	2.54	2.81	3.6
Trial 8	2.38	3.11	2.75	5.11
Trial 9	1.56	2.5	3.81	11.16
Trial 10	2.9	3.15	4.14	5.41
Mean	3.54	4.352	3.012	5.183
Std. Dev.	1.354843164	1.770328281	0.777142915	2.246009053

Table 3. Data collected using the Valkyrie model. The mean difference between Clean (0° AoA) and Dirty (0° AoA) was –0.528 seconds, a 14.9% decrease. The mean difference between between Clean (15° AoA) and Dirty (15° AoA) was 0.831 seconds, a 19.1% increase.

In order to isolate one of the variables and analyze its effect, the categories where both the configuration and angle of attack are different were not compared. For instance, Clean (0° AoA) and Dirty (15° AoA) are not compared, but Clean (0° AoA) and Dirty (0° AoA) are compared because only the configuration variable is changed. The data collected from all three models support the idea that leading-edge droop flaps increase the mean airborne time at 15° degrees angle of attack. At 0° AoA, however, both the Onslaught and Valkyrie models saw a decrease in mean airborne time.

Two p-values were also calculated for each model using the two-tail t-test – one comparing Clean (0° AoA) and Dirty (0° AoA) and the other comparing Clean (15° AoA) and Dirty (15° AoA). P-value is the probability of finding an observed difference by chance alone if there is actually no difference. In this case, they determine if the increase or decrease in airborne time with the addition of droop flaps is statistically significant at high and low angles of attack.

	p-value at 0 AoA	p-value at 15 AoA	significance level
Invader	6.33646E-05	7.41894E-06	0.05
Onslaught	0.155883196	0.000861392	0.05
Valkyrie	0.299195221	0.370305948	0.05
	p-value < 0.05	p-value > 0.05	

Table 4. The calculated p-value for Onslaught at 0° AoA and both p-values of the Valkyrie model are over the significance level, 0.05, meaning there is more than a 5% probability that the difference in airborne time with the addition of flaps is due to chance. Therefore, there is not enough evidence to show that droop flaps caused a difference in Onslaught (0° AoA) and Valkyrie's airborne time.

Conclusion

For the Invader model, droop flaps at 15° AoA increased the airborne time by 116.8%, while droop flaps at 0° AoA increased the airborne time by 66.8%. The first part of the hypothesis, that the aircraft flying at high AoAs with droop flaps will stay airborne for longer, is supported by this experiment. However, the second part of the hypothesis, that the aircraft with droop flaps will inversely affect its airborne time at low AoAs, can be rejected by the Invader model's data. Although the Invader flying at 0° AoA with droop flaps might have been flying much slower due to increased drag, its stall speed was also reduced due to the increased camber size, allowing it to stay airborne for longer. The Onslaught model also had an increase of 34.8% at 15 AoA with droop flaps, which also supports the first part of the hypothesis.

Valkyrie's high p-values show that the data was not strong enough to suggest that the increase or decrease in airborne time was caused by the addition of droop flaps. They could be explained by sampling errors, such as a small sample size, the lightness of the aircraft, or even the slightest change in wind speed or direction while the flight was airborne. Because the high p-values imply that droop flaps had no effects on Valkyrie's airborne time, this could explain why modern gliders do not have extra leading-edge devices that have minimal effects on the aerodynamic lift.

The Valkyrie model has the lowest aspect ratio, which is calculated by the wingspan squared divided by wing area. The Invader has a 1.6 ratio (8^2 / 40), the Onslaught has a 1.61 ratio (7.4^2 / 34), and the Valkyrie has a 0.98 ratio (7^2 / 50). Aircraft with lower aspect ratios tend to have less lift and more induced drag, which could have produced inconsistent data if the larger wing caught a strong gust of wind during its descent. Interestingly, the Onslaught flying at 0° AoA with droop flaps and the two Valkyrie models all saw a decrease in airborne time. However, because their data was determined to be insignificant, full conclusions cannot be made on those models because there is a high probability that the difference is produced by chance. Further experiments are thus required.

Implications

The three paper airplane models, especially the Invader and Onslaught, exhibit cropped delta wing designs. Unlike the design of modern-day airliners, a delta wing sweeps back from the aircraft body with the shape of a triangle, creating vortex lift that increases with angle of attack. For aircraft operating at supersonic speeds, the addition of leading-edge devices would not affect the L/D ratio because the vortex lift generated at high AoAs far exceeds the lift produced by leading-edge devices. At supersonic cruising speeds, any leading-edge devices extended would only increase drag.

However, leading-edge devices could greatly increase the L/D ratio of supersonic aircraft during subsonic cruise segments, such as seconds after takeoff or on final approaches and landings. For instance, the Concorde used to land at a very high AoA because enough vortex lift must be generated to keep it airborne. Although droop flaps were considered but never added to the Concorde design, such addition would have improved the aerodynamic efficiency and extended its operating range since they produce extra lift at lower speeds, increasing fuel efficiency. The AoA required to generate vortex lift significantly increases fuel burn because increasing the pitch lowers the speed, which would require more thrust to compensate due to gravity. Future supersonic aircraft such as the Boom Overture will greatly reduce travel time, but perhaps at the expense of fuel burn, pollution, and economic consequences if it is not compensated by high-lift devices at subsonic speeds.

Future Work

Future research will mainly focus on the different factors affecting aerodynamics, such as investigating trailing-edge flaps and their effects on lift and drag when extended together with leading-edge devices. There were too many variables in this paper airplane experiment that caused the high p-values, such as the lightness of the plane and its susceptibility to wind. In my next experiment, I hope to use a larger-scale remote-controlled aircraft built with solid materials and moveable high-lift devices. This will allow me to control the high-lift devices more accurately and test their effects at different speeds. Other research topics also include the positions of aircraft engines and how they affect the aerodynamic drag, which will require building different types of mini turbofan engines and attaching them to various positions on an RC aircraft.