Soaring with the Birds

Using Biomimicry to Improve The Wings of Modern Aircraft

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Purpose

Birds have often been admired for their surprising agility and fluidity in flight, and even with current technologies, we still haven't mastered flight to their extent. My project aims to bring us one step closer, by tapping into the result of 60 million years of evolution that are bird wings. By replicating features that are found on the wings of birds with flight patterns that today's aircraft require, I hope that I can further improve wings for use in commercial, recreational and rescue aircraft.

Experts

To help me better understand my topic, I successfully contacted two experts, one for each major branch of my project.

For the ornithology branch, I contacted Ivan Phillipsen, who has a PhD in zoology and a Master's degree in biology, hosts The Science of Birds podcast, and is a tour guide with Wild Latitudes. In my questions, I focused on the evolution of bird flight and the differences between bird and aircraft wings.

https://www.scienceofbirds.com/
The Science of Birds podcast, hosted by Ivan Phillipsen

is a 60% scale recreation of the historic Canadian supersonic interceptor, the Avro Arrow. Paul Gies designed the aircraft by reconstructing the original blueprints of the Arrow and improving them with current technologies. For more information, check out their website. I mostly asked about the applicability of this technology in the current market, and he suggested that fixed-wing UAVs could be a good stepping stone to bring this technology to the market, as this sector requires less testing and is much more dynamic than others.

https://www.avromuseum.com/
The Avro Museum's website with more information on the Arrow II project.

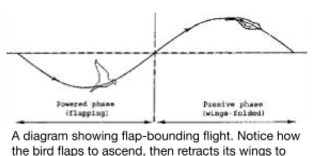
Background Research

How does bird flight differ from aircraft flight?

Due to evolutionary pressures and distinct uses, flight in birds has developed differently than in aircraft. Below are some important differences between bird and aircraft flight.

Lift Distribution

Unlike in most aircraft, birds not only use their wings to fly, but also use their aerodynamic bodies and tails to generate extra lift. If a human-made aircraft had a tail that generated constant lift, it would be very unstable, and the way birds can mitigate this will be discussed in the next section. Some small birds, such as zebra finches, take body lift to the extreme with flap-bounding flight, where the bird alternates between flapping, and just using body lift. This allows these smaller birds to fly at high speeds more efficiently. Humans have tried to adapt the concept of using the fuselage as a wing with lifting body aircraft, which are useful as reentry vehicles in aerospace, but this technology hasn't yet become applicable on the market because the design suffers at low speeds.



A diagram showing flap-bounding flight. Notice how the bird flaps to ascend, then retracts its wings to descend.

Source: Hilary A. Keating on 1 March 2002, at https://www.semanticscholar.org/paper/A-Literature-Review-on-Bounding-Flight-in-Birds-to-Keating/69e3be8a140de2686a0486428c30879518dd9352
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NASA's X-24B, built to test the applicability of lifting-body aircraft, and a predecessor of the space shuttle orbiter.

Source: NASA/Dryden, Public domain, via Wikimedia Commons

Stabilization

To maintain yaw stability, conventional aircraft have a vertical stabilizer, but birds only have a horizontal stabilizer. To remedy this, birbs actively correct themselves in flight. This also solves the issue of instability with a lift-producing horizontal stabilizer. This feat could not be achieved with a normal centralized nervous system. Even with larger brain-to-body ratios than most animals, expansions of the spinal cord still needed where nerves from the wings are connected allow birds to quickly adjust themselves in flight without needing to wait for the signal to reach the brain, in the same way that we instinctually pull away when we get burned.

Environmental Limitations

Most aircraft need a sufficiently long runway to be able to take off, but most birds don't have that luxury. Instead, they usually use the combination of a hop and "Upwards Drag" from a downstroke of their wings to take off, then land at a very high angle of attack using their alulea. Some waterfowl have access to long lake "Runways" that they can run on before takeoff, and lost the ability of immediate takeoff in favour of more aerodynamic, lower lift high-speed wings, which are suitable for long migrations flying over land. This much better matches today's aircraft, and could act as a stepping stone to biomimic birds.

Propulsion

Traditional aircraft usually use a separate propulsion system, but birds need to use their wings to produce both thrust and lift. This required many adaptations in birds, including wing permeability, because of individual feathers, and larger wing range-of-motion. This allows birds to create thrust and lift on the downstroke, and reduce downforce on the upstroke. Some larger birds, such as birds of prey and seabirds use alternate methods of propulsion that better fit with traditional aircraft, and will be described in the next section.

How have birds adapted for their individual lifestyles, and which ones are most similar to today's aircraft?

Over 60 million years of evolution, flying birds have diversified in lifestyle and habitat, and evolved four main wing types, each suited for the species' lifestyle and habitat

Elliptical Wings

Elliptical wings are highly maneuverable, create a high amount of lift at sufficient speeds, and are suitable for short bursts of high speed. These wing shapes typically belong to forest birds that need to maneuver through tight gaps in the foliage. Smaller birds with elliptical wings also use bounding flight to achieve higher speeds, by tucking in their wings and using body lift. Some examples of birds with elliptical wings are sparrows, crows, magpies, and chickadees. The Supermarine Spitfire used a similar wing shape, but this made it very difficult to manufacture.

A landing house sparrow, with elliptical wings.

Source: Eric Bégin February 2, 2010, at https://www.flickr.com/photos/ericbegin/4326900298
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High Aspect Ratio Wings

High aspect ratio wings are often used for active gliding, by catching updrafts from wind deflected by waves. The best example is the wandering albatross, one of the most efficient animals in the world. After taking off, the albatross can stay aloft by flying close to the water's surface and catching updrafts, with only a few flaps of its wings. MIT has taken inspiration from this kind of wing, and proven its feasibility with an unmanned, albatross-inspired combination of a glider and a sailboat. While high aspect ratio wings are efficient for small UAVs, they might not be applicable for heavier aircraft, because of the weight constraints of this design.

A wandering albatross in flight over water, with high aspect ratio wings

Source: Liam Quinn from Canada, CC BY-SA 2.0 <https://creativecommons.org/licenses/by-sa/2.0>, via Wikimedia Commons

Slotted High-Lift Wings

Slotted high-lift wings are often used for slow, passive gliding, and are often found on large birds of prey, such as eagles, hawks and kites. Slotted high-lift wings are deeply cambered, and are slotted at the tips to reduce drag at low speeds. These wings are useful for gliding at slow speeds or catching updrafts, without using much energy. These characteristics make slotted high-lift wings suitable for light gliders, or bush planes that need to produce lift at low speeds.

A black kite gliding, with slotted high-lift wings.

Source: Graham Winterflood July 2, 2019, at https://www.flickr.com/photos/126953422@N04/48295917476
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High-Speed Wings

High-speed wings are swept and are designed to reduce drag and still produce lift at high speeds. These wings are swept and taper to a point, to lower camber and prevent air separation at high speeds, much like fighter jets or commercial airliners. These wings are often found on migratory birds, falcons, and insectivores that need to move quickly. These wings are the most similar to modern-day wings, but many backswept-wing aircraft suffer from wingtip stall first, which could be solved with the forward sweep of the secondary wings of birds.

A peregrine falcon, the fastest animal in the world, in flight with high speed wings.

Source: Bill Abbott October 16, 2016, at https://www.flickr.com/photos/wbaiv/30609850831
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Hovering Wings

Hovering wings are found on small, fast hummingbirds, and can create lift at all times, even when stationary. They achieve this with small wings that are flapping around 70 times per second in a figure-8 movement. This is necessary for hummingbirds because of their diet of hard-to-access nectar. Many attempts have been made to replicate this motion, but the high energy needed might make this design hard to use for aircraft.

A Ruby-Throated hummingbird hovering in front of a flower.

Source: Sascha Wenninger, CC BY-SA 2.0 <https://creativecommons.org/licenses/by-sa/2.0>, via Wikimedia Commons

Overall, I chose to test aspects of slotted high-lift and high-speed wings, because they best fit the requirements of commercial, recreational and rescue aircraft.

What problems do today's airfoils face, how have we countered them, and what bird adaptations could help?

Wing Tip Vortices

The Problem

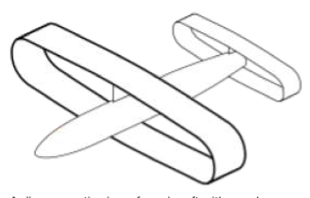
One way the wing generates lift is by causing a pressure difference between the top and bottom of the wing, by both Bernoulli's principle and the wing's angle of attack. The high pressure below the wing pushes the wing up into the low-pressure zone in an attempt to equalize the pressure, which can be harnessed as lift. This works on most of the wing, but near the wingtips, the path of least resistance is to flow spanwise, which is parallel to the wing, and around the wingtip to equalize. This renders the wingtips "Ineffective", as the pressure differential isn't creating any lift. In addition, this flow also produces drag and spins the air behind it, forming vortices that expand as they move further from the aircraft. This effect decreases as the speed increases, as the air spends less time separated by the wing.

The wingtip vortices produced by an agricultural plane in a NASA study

Source: NASA Langley Research Center (NASA-LaRC), Edited by Fir0002, Public domain, via Wikimedia Commons

How Current Aircraft Have Countered This

People have recognized this problem and have tried to solve it, usually by strategically adding extra wing area. For example, winglets are small wings added to the wingtips and are usually curved upwards. These provide an extra barrier for air trying to flow around the wingtip, as it has to flow around the wingtips before it reaches the low-pressure zone on top of the wing. Another solution is the addition of wing fences, which are vertical surfaces on the wing that limit the spanwise flow that is required for air to reach the wingtips. Some newer solutions aim to eliminate the wingtips entirely, by making the wing a continuous loop around the fuselage. This is called a closed wing, and can either wrap around the whole aircraft or just the wing tips. This design also comes with the added benefit of being able to fit more wing in the same space. Even with these advantages, closed-wing aircraft still have to solve many issues before they can be widely accepted.

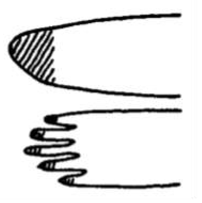


A diagrammatic view of an aircraft with annular closed wings

Source: Steelpillow, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Bird Adaptations That Could Help

Large birds of Prey glide slowly and passively, so drag caused by wing vortices is a large problem. Their low speed gives the air a lot of time to move toward the wingtips and form vortices, and they can't get that energy back because of their gliding lifestyle. To counter this, they have notched wingtips to reduce the wingtip area where vortices form. This reduces the "Ineffective" area of the wing, which both increases lift and reduces drag. Slow-flying aircraft, such as gliders or bush planes, could benefit from this kind of wing, as they have similar limitations as birds of prey.



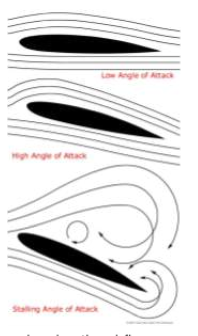
A comparison of the "Ineffective" area of a wing with and without tip slotting.

Source: D. B. O. SAVILB
Botany and Plant Pathology Laboratory, Science Service, Ottawa, Ontario, Canada, on November 9, 1956, at https://www.jstor.org/stable/2406051

Airflow Separation

The Problem

Another way an airfoil generates lift is by pushing air downwards, and by Newton's third law, this exerts an upward force on the airfoil. The airfoil does this in two ways. The first way is the bottom surface acting as a ramp, pushing the air down, and the second way is by the Coanda effect, which describes the tendency for moving fluids to stick to a surface, like the upper surface of the wing. When the angle of attack of the wing is too high, the airflow's inertia overpowers the Coanda effect, which results in the airflow flowing away from the wing, and a low-pressure zone forming where the airflow was. This is known as a boundary layer separation, and results in a loss of lift and increased drag.



A diagram showing the airflow around an airfoil at different angles of attack. Note the turbulent break-away at the stalling angle of attack.

Source: The Aviation History Online Museum, at http://www.aviation-history.com/theory/angle_of_attack.htm

How Current Aircraft Have Countered This

Current aircraft solve this problem in two main ways: Reducing the angle of attack required to create extra lift, and increasing the airflow momentum to keep the airflow stuck to the upper surface. Extra lift at lower angles of attack can be achieved with an undercambered wing, which helps gently guide air down over the upper surface of the wing. This wing shape isn't applicable for all aircraft and situations, so flaps and dropped leading edges can be used to change the wing shape into an undercambered wing mid-flight. A new, innovative design uses a more biological approach, by flexing the wing into the desired shape. These are known as flexible leading-edge devices and can warp the wing from a regular shape into an undercambered airfoil. As for the other method, there are a few ways to increase the air's momentum. One way is to use slots, which are strategically shaped and placed holes in the wing, and direct a stream of high-pressure air over the upper surface of the wing to reinforce the Coanda effect. Another method is to use vortex generators to slow the air down and use that energy to create vortices that reinforce the Coanda effect.

Bird Adaptations That Could Help

First evolved in the early Cretaceous in the early ancestor of birds Eoalulavis hoyasi, alulea are found on almost all modern flying birds, suggesting that they are crucial for bird flight. The alula is a small cluster of feathers attached to the "thumb" of the wing and acts as both a slat and a vortex generator when extended, much like modern aircraft. They act as a small wing, redirecting a high-pressure jet of air over the wing, and generating wingtip vortices in the same manner as discussed above. This allows birds to create lift and drag at high angles of attack without the airflow separating to achieve the fast and stationary landings that are required for their lifestyles.

Responding Variables

These are the variables that I will be measuring for each iteration so that the results can be easily compared

Lift Produced

The lift produced is the amount of upward force generated by the wing. This also measures the amount of weight the wing can carry. I will be measuring the lift in newtons, which is about the force required to lift 100g in Earth's gravity.

Lift to Wing Area ratio

The lift-to-wing-area ratio expresses how much lift each unit area of the wing is generating. This is useful, as it shows a more generalized view of the wing's effectiveness, and compensates for the uncontrolled area of the wing, especially for wings with wingtip slots. I will be using the unit N/m^2, which expresses how many newtons of lift the wing would produce if it had $1m^2$ of surface area.

Stall Angle

The stall angle is the angle of attack at which airflow separation occurs, which was described in the background research. When the wing reaches this angle, it experiences a sudden drop in lift, which could be dangerous for aircraft. I will be measuring the lift of the wing at increasing angles of attack until it drops, which will be the stall angle

Hypothesis

If adaptations found on birds that assist flight are added to traditional airfoils, then the lift, lift-to-wing-area ratio, and stall angle will increase because, throughout their 60 million years of evolution, birds have evolved adaptations that suit their individual lifestyles, many of which require more versatile and efficient wings than today's aircraft.

Standardized Procedure

These are the procedures I will use to consistently determine and compare the lift produced, lift-to-wing-area ratio, and the stall angle of the wings in each iteration.

Lift produced and Lift-to-Wing-Area Ratio Procedure

1. Place the control airfoil in the wind tunnel lock, as shown:

2. Set the angle of attack pointer to 10°
3. Insert the cardboard spacing chip behind the angle of attack pointer to secure it
4. Press zero on the lift scale
5. Wait until the lift scale reading is stable
6. Take note of the lift scale reading
7. Set wind tunnel fan speed to 3
8. If the scale reading does not change, the data collection system might be snagged in the cardboard notch, and nudge the data collection system into the wind.
9. Wait until the lift scale reading is stable
10. Take note of the lift scale reading
11. Turn off the wind tunnel fan
12. Remove the airfoil from the lock
13. Repeat steps 1-12 with all remaining airfoils
14. Repeat steps 1-13 for 5 trials, to ensure consistency

Stall Angle

I only ran this experiment for one trial because all data collected is either relative or qualitative.

1. Place the control airfoil in the wind tunnel lock, as done before
2. Set the angle of attack pointer to 0°
3. Insert the cardboard spacing chip behind the angle of attack pointer to secure it
4. Press zero on the lift scale
5. Wait until the lift scale reading is stable
6. Take note of the lift scale reading
7. Set wind tunnel fan speed to 3
8. If the scale reading does not change, the data collection system might be snagged in the cardboard notch, and nudge the data collection system into the wind.
9. Wait until the lift scale reading is stable
10. Take note of the lift scale reading
11. Using the thread, take note of airflow around the wing
12. Turn off the wind tunnel fan
13. Set the angle of attack pointer up a mark
14. Repeat steps 1-12 until the pointer is at 90°
15. Note the angle of attack
16. Remove the airfoil from the lock
17. Repeat steps 1-16 for all remaining airfoils

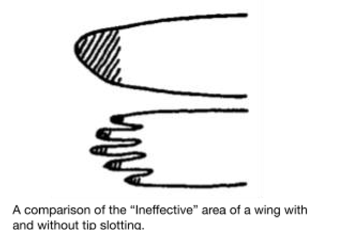
Design Iterations

Iteration 1

Inspiration: Rectangular, slotted wings of the Order Accipitriformes

Ideas

The order Accipitriformes contains most large birds of prey, including eagles, hawks, vultures, etc. They have slotted high-lift wings, suitable for low-power gliding and catching updrafts, and can create lift at low speeds while preventing vortex-induced drag. This is achieved using a deeply cambered wing with notches near the wingtip. These notches reduce the wingtip area, giving the air a smaller area to flow around and form vortices. The reduction in wingtip vortices not only reduces the drag caused by the creation of vortices, but also increases lift by increasing the pressure difference between the two sides of the wing.



A comparison of the “Ineffective” area of a wing with and without tip slotting.

Source: D. B. O. SAVILB
Botany and Plant Pathology Laboratory, Science Service, Ottawa, Ontario, Canada, on November 9, 1956, at https://www.jstor.org/stable/2406051

A red shouldered hawk in flight. Note the rectangular wing shape and spread out feathers on the wing tip.

Source: FotoFloridian May 26, 2019, at https://www.flickr.com/photos/fotofloridian/48102794668/
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Adding wingtip slots to aircraft could be used to increase lift and reduce drag, without adding much more wing.

Testing

The Effects of Adding Wingtip Slots On The Lift-to-Wing-Area Ratio, the Lift Produced, and the Stall Angle of a Traditional Airfoil

Problem

Can wing slots similar to those found on some birds affect the lift created by each cm^2 of a traditional airfoil?

Hypothesis

If the number of wing-tip slots increases, the lift will decrease slightly but the lift-to-wing-area ratio will increase, because the wing will have less lift area, but also have less area overall, and less energy is wasted by generating wingtip vortices, leaving more energy for lift.

If the number of wing-tip slots increases, then the stall angle will remain the same, because even at the wing tips, the individual wing cross sections are always congruent, and airflow will separate at the same angle.

Variables

Manipulated: Number of wing tip slots (0,1,2)
Responding:
- Lift to Wing Area ratio
- Lift Produced
- Stall Angle

Controlled:
- Wing
  - Chord Length: 4cm
  - Camber Length: 1cm
  - Wing Span: 15 cm
  - Wing cross section up until 5cm away from the wing root (Symmetrical)
- Wingtip Slots
  - Transitional area to the wing tip slots (Tapering airfoils “clipped” together)
  - Shape of wing tip slots: Triangular, airfoil splits into smaller, tapered airfoil
  - Wing tip slot depth (5cm)
- Airflow in wind tunnel (Max)

Materials

- Small wind tunnel with adjustable angle of attack and lift reading
- 3-D printed models of 4 identical airfoils with 0,1 or 2 wing tip slots
- Red sewing thread attached to the end of a skewer
- Cardboard spacer chip

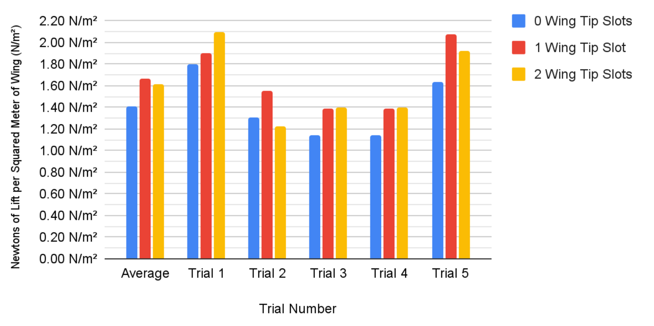
Procedure

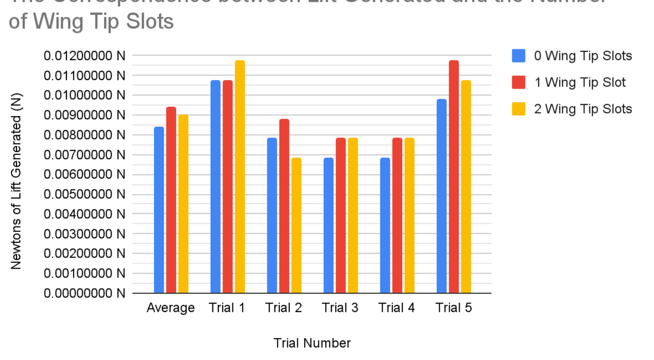
Standardized testing procedure was used, refer to the “Standardized Procedures” section on the first panel.

Observations

How the amount of wing slots affects the lift to wing area ratio and the lift produced:

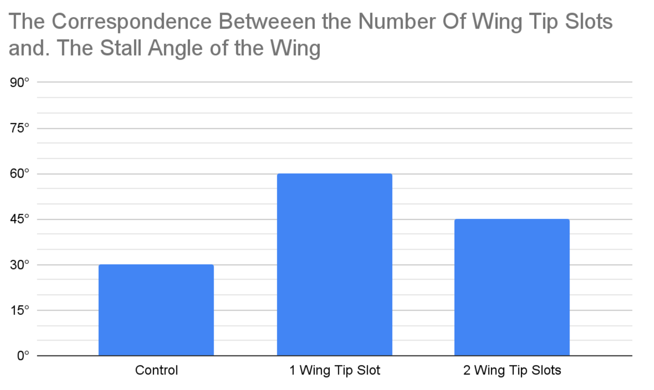
Trial	Wing tip Slots	Wing Area	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Lift (in Newtons) to Wing Area
1	0	60.00 cm²	0.00 g	-1.10 g	0.011 N	1.7978858 N/m²
	1	56.67 cm²	0.00 g	-1.10 g	0.011 N	1.9036438 N/m²
	2	56.00 cm²	0.00 g	-1.20 g	0.012 N	2.1014250 N/m²
2	0	60.00 cm²	0.00 g	-0.80 g	0.008 N	1.3075533 N/m²
	1	56.67 cm²	13.00 g	12.10 g	0.009 N	1.5575268 N/m²
	2	56.00 cm²	0.00 g	-0.70 g	0.007 N	1.2258313 N/m²
3	0	60.00 cm²	5.70 g	5.00 g	0.007 N	1.1441092 N/m²
	1	56.67 cm²	5.60 g	4.80 g	0.008 N	1.3844682 N/m²
	2	56.00 cm²	26.60 g	25.80 g	0.008 N	1.4009500 N/m²
4	0	60.00 cm²	-0.70 g	-1.40 g	0.007 N	1.1441092 N/m²
	1	56.67 cm²	0.00 g	-0.80 g	0.008 N	1.3844682 N/m²
	2	56.00 cm²	3.10 g	2.30 g	0.008 N	1.4009500 N/m²
5	0	60.00 cm²	0.00 g	-1.00 g	0.010 N	1.6344417 N/m²
	1	56.67 cm²	1.20 g	0.00 g	0.012 N	2.0767024 N/m²
	2	56.00 cm²	0.60 g	-0.50 g	0.011 N	1.9263063 N/m²
AVG	0	60.00 cm²	1.00 g	0.14 g	0.008 N	1.4056198 N/m²
	1	56.67 cm²	3.96 g	3.00 g	0.009 N	1.6613619 N/m²
	2	56.00 cm²	6.06 g	5.14 g	0.009 N	1.6110925 N/m²





How the number of wing tip slots affect the stall angle of the wing

Alula Angle	Stall Angle
Control	30°
1 Wing Tip Slot	60°
2 Wing Tip Slots	45°



Analysis

Overall, the wing with 1 wing tip slot performed the best in both lift and lift-to-wing-area ratio. Trail 1 seems to be an outlier because every wing performed much better than trials 2,3 and 4, and the lift produced by 2 wing tip slots exceeds the lift produced by 1 wing tip slots more than others. This might have been caused by the data collection system slider being stiffer or looser than usual. Trial 5 might also be an outlier because of similar reasons, except for the large jump in lift with 1 wing tip slot. The results of trials 3 and 4 are exactly the same, which might be a coincidence, or they might have been controlled very well.

The wing with one wing tip slot also had the highest stall angle, and the control had the lowest. I had a problem with the high drag of the wings causing the data collection system to catch in its notch, disabling the scale readings.

Conclusion

My hypothesis was partially correct because the lift-to-wing-area ratio did increase when wingtip slots were first added, but decreased when the second slot was added, contrary to my hypothesis, which predicted that the lift-to-wing-area ratio would always increase with added wingtip slots. My hypothesis also predicted that the lift would decrease slightly as the number of wing tip slots increased, but in reality, the lift followed a similar pattern to the lift-to-wing-area ratio.

My second hypothesis was incorrect because the wing with 1 wingtip slot had the highest stall angle. This might be due to the front “Feather” acting like a leading edge slot. Which forces a jet of high-pressure air over the second “Feather”, preventing air separation even after the main wing stalls. According to this, the same effect should be working on the wing with 2 wing tip slots, but it still has a lower stall angle. This might be because the “Feathers” are too thin to produce sufficient lift after the main wing stalls.

Overall, an added wing tip slot greatly improved the performance of the wing, and could be used to replace bulky winglets and wind fences.

Extension

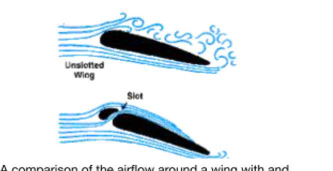
From my background research, the addition of wing tip slots increases the pressure differential, and with it, lift, by reducing the wing tip area for air to go around. I might try to change the area of the wingtip by adjusting the taper of the “Feathers”, and see how that affects lift. I might also replicate the upward curve of eagle feathers, much like current winglets. Another way I could replicate the wings of large raptors is to use “Square” notches instead of the triangular ones I’m using now, which will allow for more even airflow through the slot, and reduce drag caused by air flowing through the narrow part of the slot. I could also reduce the wing tip area by tapering the wing to a sharp point, like on high-speed found on terns and falcons.

Iteration 2

Inspiration: Alulea, found in almost all flying birds, first evolved during the early Cretaceous.

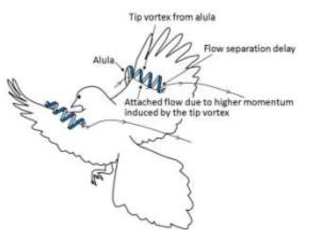
Ideas

On a bird’s wing, the alula is a small piece of the wing attached to its “Thumb”. It is raised during landing to form a slot, much like leading edge slots and vortex generators on today’s aircraft, to prevent airflow separation and extra drag at high angles of attack by shooting a jet of high-pressure air over the upper surface of the wing to reinforce the Coanda effect and generate vortices over the wing to increase the air’s momentum. During regular flight, the alulas are typically flattened to the wing to reduce drag. Alulas seem to be a crucial part of flight, as they evolved very early in bird evolution, and are much better at preventing airflow separation than leading edge slots, as seen during the high angle-of-attack landings that birds require.



A comparison of the airflow around a wing with and without slotting. Note the turbulent break-away of airflow over the unslotted wing.

A Western jackdaw in the process of landing. Note the alulea an the leading edge of the wing



A diagram showing vortices formed by the alulea attaching airflow to the wing’s upper surface.

Source: Sang-im Lee, Jooha Kim, Hyungmin Park, Piotr G. Jabłoński & Haecheon Choi on 07 May 2015, at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4423427/
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Adding alulea to the wings of aircraft. could allow higher angle-of-attack, and therefore shorter landings.

Testing

How does the Angle of added Alulea affect lift to wing area ratio, the Lift Produced, and the Stall Angle on traditional airfoils in a wind tunnel

Problem

Can added alulea similar to those found on most birds affect the stall angle of a traditional airfoil? If so, can the angle of the alula increase or decrease the stall angle further?

Hypothesis

If the angle of attack of the alula decreases, then the stall angle will increase because the larger pressure differential between the top and bottom of the alula will increase, creating a stronger vortex over the upper surface of the wing, which will increase the air’s momentum and prevent air separation, and the lower angle of attack will prevent the alula from stalling.

If the angle of attack of the alula increases, then the lift produced will increase because the alula deflects air downwards, and creates more lift via Newton’s third law of motion.

Variables

Responding:
- Lift to Wing Area ratio
- Lift Produced
- Stall Angle

Controlled:
- Basic Wing:
  - Chord Length: 4cm
  - Camber Length: 1cm
  - Wing Span: 15 cm
  - Wing cross section up until 5cm away from the wing root (Symmetrical)
- Alula Shape
  - Chord Length: 1cm
  - Camber Length: 0.25cm
  - Wing Span: 3 cm
  - Wing cross section up until 5cm away from the wing root (Symmetrical)
- Airflow in wind tunnel (Max)

Materials:

- Small wind tunnel with adjustable angle of attack and lift reading
- 3-D printed models of 4 identical airfoils with alulea that have -20°, -10°, 0°, and 10° alula angles
- 3-D printed model of control airfoil
- Cardboard spacer chip

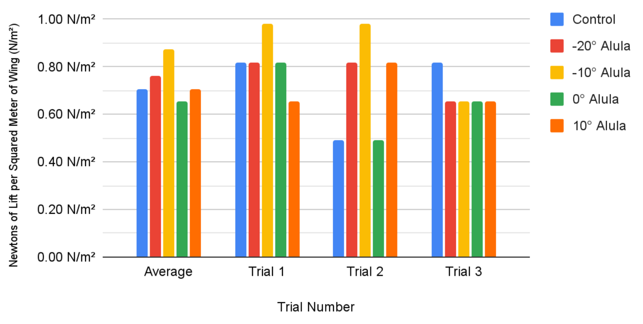
Procedure

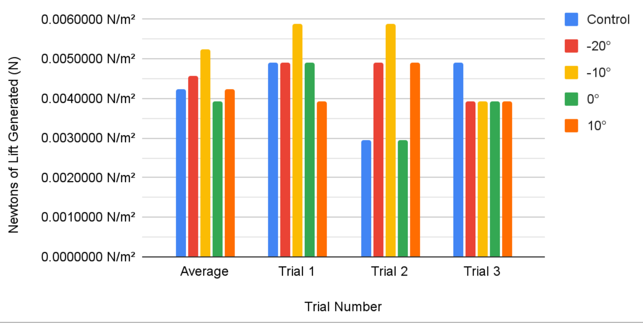
Standardized testing procedure was used. refer to the “Standardized Procedures” section on the first panel.

Observations

The Affects of Different Alula Angles on The Lift-to-Wing-Area Ratio and The Lift Produced:

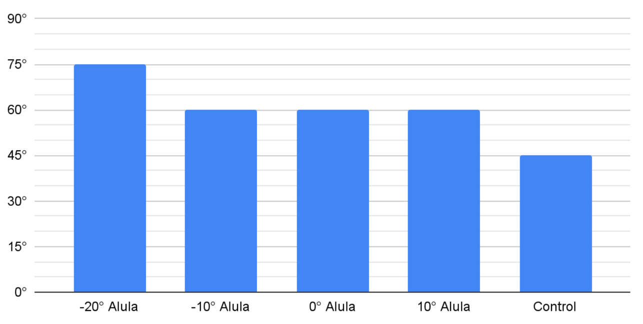
Trial	Alula AOA°	Wing Area	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Lift (in Newtons) to Wing Area
1	Control	60.00 cm²	-1.70 g	-2.20 g	0.005 N	0.8172208 N/m²
	-20°	60.00 cm²	0.50 g	0.00 g	0.005 N	0.8172208 N/m²
	-10°	60.00 cm²	-1.20 g	-1.80 g	0.006 N	0.9806650 N/m²
	0°	60.00 cm²	4.20 g	3.70 g	0.005 N	0.8172208 N/m²
	10°	60.00 cm²	1.2	0.8	0.004 N	0.6537767 N/m²
2	Control	60.00 cm²	-1.00 g	-1.30 g	0.003 N	0.4903325 N/m²
	-20°	60.00 cm²	-4.40 g	-4.90 g	0.005 N	0.8172208 N/m²
	-10°	60.00 cm²	-0.60 g	-1.20 g	0.006 N	0.9806650 N/m²
	0°	60.00 cm²	2.00 g	1.70 g	0.003 N	0.4903325 N/m²
	10°	60.00 cm²	-3.9	-4.4	0.005 N	0.8172208 N/m²
3	Control	60.00 cm²	-1.90 g	-2.40 g	0.005 N	0.8172208 N/m²
	-20°	60.00 cm²	-2.70 g	-3.10 g	0.004 N	0.6537767 N/m²
	-10°	60.00 cm²	-0.60 g	-1.00 g	0.004 N	0.6537767 N/m²
	0°	60.00 cm²	-0.40 g	-0.80 g	0.004 N	0.6537767 N/m²
	10°	60.00 cm²	-6.7	-7.1	0.004 N	0.6537767 N/m²
AVG	Control	60.00 cm²	-1.53 g	-1.97 g	0.004 N	0.7082581 N/m²
	-20°	60.00 cm²	-2.20 g	-2.67 g	0.005 N	0.7627394 N/m²
	-10°	60.00 cm²	-0.80 g	-1.33 g	0.005 N	0.8717022 N/m²
	0°	60.00 cm²	1.93 g	1.53 g	0.004 N	0.6537767 N/m²
	10°	60.00 cm²	-3.13 g	-3.57 g	0.004 N	0.7082581 N/m²





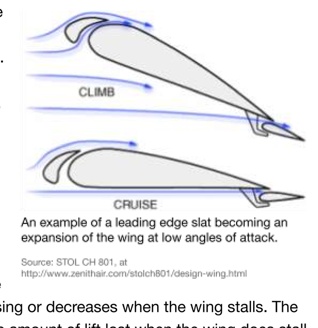
The Effects of Different Alula Angles on The Stall Angle of the Wing

Alula Angle	Stall Angle
-20° Alula	75°
-10° Alula	60°
0° Alula	60°
10° Alula	60°
Control	45°



Analysis

At the angle of attack of 10°, the wing with a -10° alula created the most lift. This could be because the alula would be at a 0° angle of attack, which prevents disruption of airflow over the main wing. Airflow around the wing with the -20° alula might have not flowed into the slot formed by the wing, instead flowing around the alula, effectively expanding the wing. Both the 0° and 10° alulea could have caused enough disruption to reduce the lift of the wing, but the 10° alula might have also created enough lift to compensate as a regular airfoil.



An example of a leading edge slat becoming an expansion of the wing at low angles of attack.

In all the stall angle tests, the lift increases as the angle of attack increases, and then stops increasing or decreases when the wing stalls. The addition of alulea delays stalling, and reduces the amount of lift lost when the wing does stall. The -20° alula stalled last because more of the alula was in direct airflow when the wing is at a high angle of attack, and still be effective when other alulea are blocked by the main wing.

Conclusion

My first hypothesis was correct, because added alulea increased the stall angle, and the stall angle increased as the alula angle decreased.

My second hypothesis was incorrect because the lift didn’t increase with the alula angle of attack all the time, instead, the -10° alula performed the best, possibly because it has a 0° angle of attack when the wing is at a 10° angle of attack. The 10° alula was an improvement from the 0° alula, but not large enough of an improvement to overtake the -10° alula.

Extension

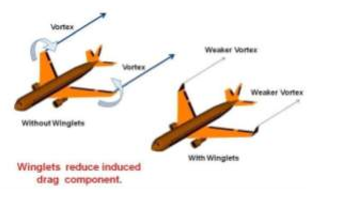
The alulea as tested here can be used to prevent stalling during takeoffs and landings, when the wings are the most susceptible to stalling because of the high angles of attack and low speed. Alulea could also allow aircraft to fly at even higher angles of attack during landing, which means that they can still create lift at low speeds, and therefore land on shorter runways. I could test the interactions between the alula and the wingtip slots in future experiments, and tweak the alula to create more lift or wingtip vortices, and increase the stall angle further.

Iteration 3

Inspiration: Wingtip slots formed by individual flexible feathers, and winglets of modern aircraft

Ideas

After the success of wing tip slots in iteration 1, I want to improve on that design with some extra vortex-reducing wingtip devices. In both current aircraft and some gliding birds, the wingtips are curved upwards, forcing high-pressure air to move up to the wingtips to reach the low-pressure zone, and also reduce the pressure differential between the top and bottom surfaces of the wingtips. These are called winglets and help maintain the pressure differential between the wing surfaces, and reduce the creation of wingtip vortices. By doing this, the winglets can help the wing generate more lift while reducing drag.



A comparison of wingtip vortices created by an aircraft with and without winglets.

Source: NASA Glenn Research Center, Beginners Guide to Aeronautics

A Bald Eagle in gliding flight. Note the upward curve of the wingtip feathers.

Source: National Park Service
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Testing

The Effects of Adding Alulea With Different Angles On The Lift-to-Wing-Area Ratio, the Lift Produced, and the Stall Angle of a Traditional Airfoil

Problem

How does adding winglet-like tips to the “Feathers” of an Airfoil with one wingtip slot affect its lift and stall angle?

Hypothesis

If the winglet-like tips are added to the “Feathers” of the slotted airfoil, then the lift produced and the lift-to-wing-area ratio will increase because the curved winglet provides a pressure gradient to the wingtips, and forces high-pressure air to move further before reaching the low-pressure zone, and also reduce the pressure difference between the upper and lower parts of the wing, and reduce wingtip vortices.

If the winglet-like tips are added to the “Feathers” of the slotted airfoil, then the stall angle will remain the same, because the airfoil’s cross-section will remain the same, and not change the airflow around itself.

Variables

Manipulated: Winglet Present
Responding:
- Lift to Wing Area ratio
- Lift Produced
- Stall Angle

Controlled:
- Basic Wing:
  - Chord Length: 4cm
  - Camber Length: 1cm
  - Wing Span: 15 cm
  - Wing cross section up until 5cm away from the wing root (Symmetrical)
  - 1 wing tip slot
- Winglet Angle (30°)
- Airflow in wind tunnel (Max)

Materials:

- Small wind tunnel with adjustable angle of attack and lift reading
- 3-D printed models of 2 identical airfoils with 1 wingtip slot, but one has winglets
- 3-D printed model of control airfoil
- Cardboard spacer chip

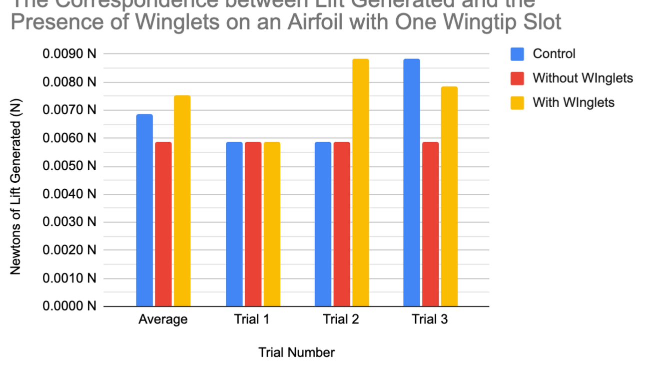
Procedure

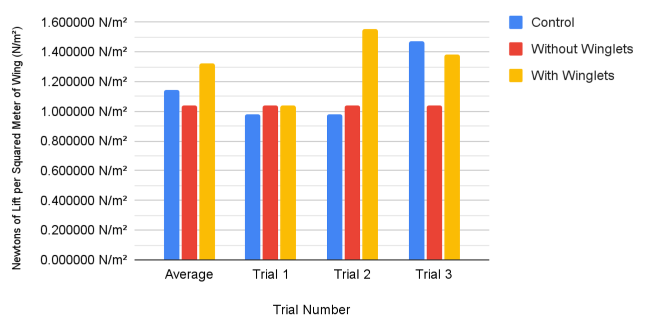
Standardized testing procedure was used. refer to the “Standardized Procedures” section on the first panel.

Observations

How the angle of attack of the alulea affects the lift-to-wing area ratio and the lift produced:

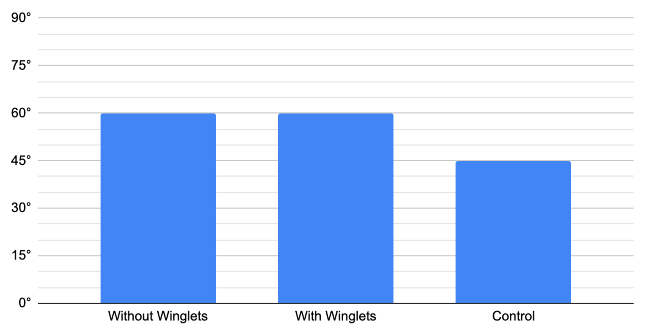
Trial	Alula AOA°	Wing Area	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Lift (in Newtons) to Wing Area
1	Control	60.00 cm²	0.60 g	0.00 g	0.006 N	0.9806650 N/m²
	Without Winglets	56.67 cm²	1.40 g	0.80 g	0.006 N	1.0383512 N/m²
	With Winglets	56.67 cm²	0.60 g	0.00 g	0.006 N	1.0383512 N/m²
2	Control	60.00 cm²	0.60 g	0.00 g	0.006 N	0.9806650 N/m²
	Without Winglets	56.67 cm²	0.60 g	0.00 g	0.006 N	1.0383512 N/m²
	With Winglets	56.67 cm²	0.50 g	-0.40 g	0.009 N	1.5575268 N/m²
3	Control	60.00 cm²	0.00 g	-0.90 g	0.009 N	1.4709975 N/m²
	Without Winglets	56.67 cm²	0.60 g	0.00 g	0.006 N	1.0383512 N/m²
	With Winglets	56.67 cm²	3.90 g	3.10 g	0.008 N	1.3844682 N/m²
AVG	Control	60.00 cm²	0.40 g	-0.30 g	0.007 N	1.1441092 N/m²
	Without Winglets	56.67 cm²	0.87 g	0.27 g	0.006 N	1.0383512 N/m²
	With Winglets	56.67 cm²	1.67 g	0.90 g	0.008 N	1.3267821 N/m²





The Impact Of the Presence of Winglets On the Stall Angle of a Wing With 1 Wingtip Slot

Alula Angle	Stall Angle
Without Winglets	60°
With Winglets	60°
Control	45°



Analysis

Contrary to previous tests, the wing with one wingtip slot performed worse than the control airfoil in both the lift and lift-to-wing-area ratio tests, but the winglets compensated for this loss of lift, performing even better than the control airfoil. This loss of lift could be caused by the uneven airflow throughout the triangular wing slot, especially through the wider portion. This could be optimized with a rectangular slot, like found on large gliding raptors. The extra lift generated by the winglets could have been due to the winglets reinforcing the vortex-reducing effect of the wingtip slots, but also doesn’t let air too much airflow through the larger parts of the wingtip slot, as the winglets don’t generate a large pressure differential.

There is not much of a pattern between the trials, but the relations between the different wings seem similar for each trial. The small inconsistencies in the lift readings between trials could have been caused by inaccuracies in the scale readings or changes in the data collection system slider. These inconsistencies would be reduced by averaging out the trials.

All the lift at different angles of attack followed a similar pattern, increasing until the stall angle, then decreasing. The wings with two wingtip slots performed the same in terms of stall angle, as their slots work in the same way to prevent airflow separation.

Conclusion

Both of my hypotheses were correct, as the lift and stall angle did increase with the introduction of the wingtip slot and winglets. This is because of the wingtip slots and winglets prevent the loss of the pressure difference over the two wing surfaces, and the wingtip slots increase the inertia of the airflow over the upper wing surface. Along with this, the curved wingtip would also form a dihedral, which keeps the aircraft stable in the roll axis by providing offset lift.

Overall, the addition of a “Feather-like” wingtip improved the wing’s lift and stability greatly.

Extension

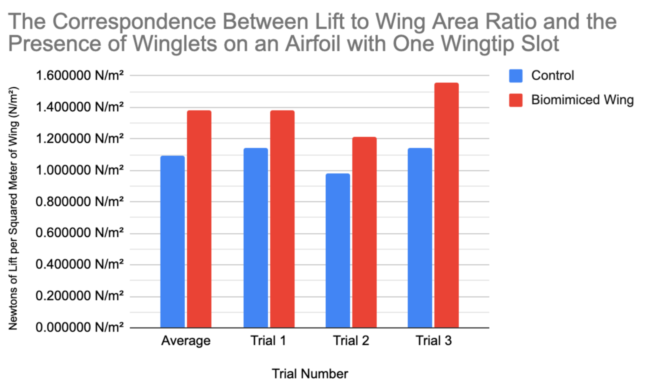
I might try to change the area of the wingtip by adjusting the taper of the “Feathers”, and see how that affects lift, or narrow the tip to a point, to eliminate the wingtip completely. I could also adapt the square slots mentioned earlier, to ensure optimal airflow throughout the slot.

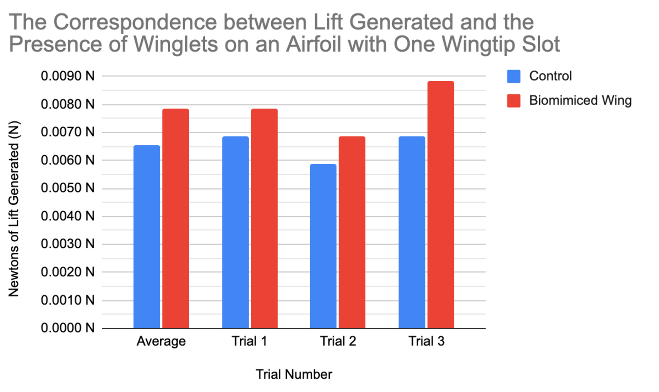
Final Results

Observations

How the angle of attack of the alulea affects the lift-to-wing area ratio and the lift produced:

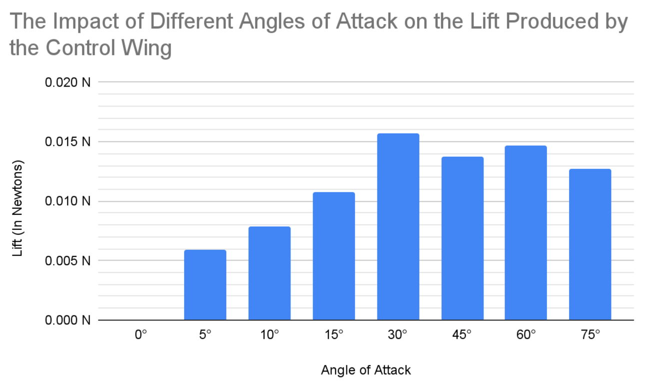
Trial	Alula AOA°	Wing Area	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Lift (in Newtons) to Wing Area
1	Control	60.00 cm^2	0.70 g	0.00 g	0.007 N	1.1441092 N/m^2
	Biomimiced Wing	56.67 cm^2	0.80 g	0.00 g	0.008 N	1.3844682 N/m^2
2	Control	60.00 cm^2	3.60 g	3.00 g	0.006 N	0.9806650 N/m^2
	Biomimiced Wing	56.67 cm^2	3.70 g	3.00 g	0.007 N	1.2114097 N/m^2
3	Control	60.00 cm^2	0.70 g	0.00 g	0.007 N	1.1441092 N/m^2
	Biomimiced Wing	56.67 cm^2	2.00 g	1.10 g	0.009 N	1.5575268 N/m^2
AVG	Control	60.00 cm^2	1.67 g	1.00 g	0.007 N	1.0896278 N/m^2
	Biomimiced Wing	56.67 cm^2	2.17 g	1.37 g	0.008 N	1.3844682 N/m^2





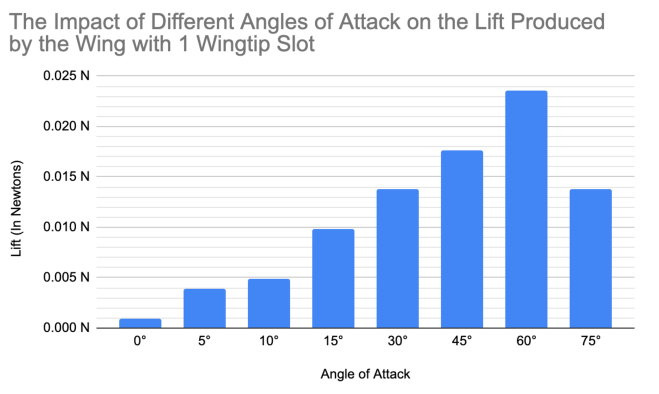
The Effects of Different Angles of Attack on Lift and Airflow Around a Control Wing

Angle of Attack	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Airflow (Qualitative)
0°	0.90 g	0.90 g	0.000 N	Airflow is laminar and barely affected by the wing
5°	0.00 g	-0.60 g	0.006 N	Airflow is laminar and slightly deflected by the wing
10°	0.80 g	0.00 g	0.008 N	Airflow is slightly turbulent, but still mostly laminar, and follows the airfoil shape
15°	0.40 g	-0.70 g	0.011 N	Airflow is slightly turbulent, but still mostly laminar, and follows the airfoil shape
30°	0.80 g	-0.80 g	0.016 N	Airflow is slightly turbulent, but still mostly laminar, and clearly follows the airfoil shape
45°	0.50 g	-0.90 g	0.014 N	The airflow is very turbulent, and spanwise flow is present near the wingtips
60°	0.30 g	-1.20 g	0.015 N	The airflow is very turbulent, and air flows backwards over and after the wing
75°	0.00 g	-1.30 g	0.013 N	The airflow is very turbulent, and air flows backwards after the wing
		Stall Angle:	45°	



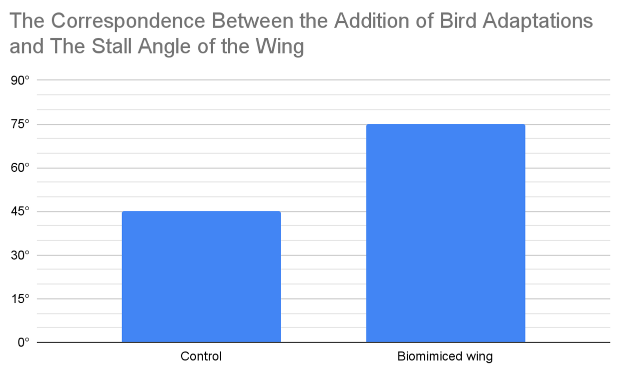
The Effects of Different Angles of Attack on Lift and Airflow Around a Wing With Added Bird Adaptations

Angle of Attack	Scale Reading (No Wind)	Scale Reading (With Wind)	Lift (In Newtons)	Airflow (Qualitative)
0°	1.30 g	1.20 g	0.001 N	Airflow is laminar and barely affected by the wing. Airflow also flows over the alula
5°	1.50 g	1.10 g	0.004 N	Airflow is laminar and barely affected by the wing. Airflow also flows over the alula
10°	1.50 g	1.00 g	0.005 N	Airflow is laminar and slightly deflected by the wing. Airflow also flows over the alula
15°	1.00 g	0.00 g	0.010 N	Airflow is laminar and follows the shape of the wing. Spanwise flow by the alula tip is also present.
30°	1.40 g	0.00 g	0.014 N	Airflow is laminar and follows the shape of the wing. Spanwise flow by the alula tip is also present.
45°	1.80 g	0.00 g	0.018 N	Airflow is turbulent, but more laminar over the alula. Spanwise flow by the alula tip is also present.
60°	2.40 g	0.00 g	0.024 N	Airflow is very turbulent, and flows backwards sometimes, but less so over the alula. Spanwise flow by the alula tip is also present.
75°	1.40 g	0.00 g	0.014 N	Airflow is very turbulent, and flows backwards sometimes over the whole wing.
		Stall Angle:	75°	



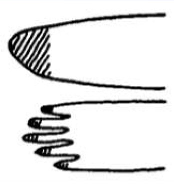
The Effects of Added Bird Adaptations on the Stall Angle of a Traditional Airfoil

Alula Angle	Stall Angle
Control	45°
Biomimiced wing	75°



Analysis

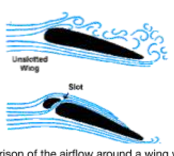
Over all three trials, the biomimiced wing generated an average of 27% more lift than the traditional airfoil. This trend was very regular over all three trials, except for trial 3, where the biomimiced airfoil generated 37% more lift than the traditional airfoil. This increase of lift is caused by the winglets and wingtip slot preventing the production of wingtip vortices and maintaining the pressure differential by reducing the wingtip area for vortices to form, and reducing the pressure differential near the wingtip. The alula was also in front of the wing, which might have extended the effective lift area of the wing. The winglets also provide the added benefit of adding a small dihedral, which prevents the aircraft from rolling, providing stability.'



A comparison of the "Ineffective" and vortex-generating area of a wing with and without tip slotting.

Source: D. B. O. SAVILB
Botany and Plant Pathology Laboratory, Science Service, Ottawa, Ontario, Canada, on November 9, 1956, at

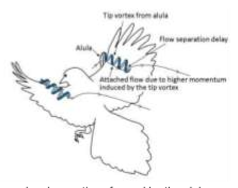
The stall angle also surpassed the control airfoil by almost 2 times. This could be because the alula and the wingtip slot shoot a high-pressure jet of air along most of the wing, which reinforces the Coanda effect, and keeps air stuck to the upper surface of the wing. The wing slots means that most of the wing was still generating lift, which resulted in a maximum lift of 0.024N, compared to a peak lift of 0.015N with only alulea. This could allow the wing to land at very low speeds at a high angle of attack, reducing the area required for landing.



A comparison of the airflow around a wing with and without a leading edge slat, which proforms a similar role to the alula. Note the turbulent break-away of airflow over the unslotted wing.

Source: Vera C. Teschow 2/24/2011, at
http://flyonline.weebly.com/blog/slats-and-slots

Overall, the addition of bird adaptations greatly boosts the performance of the wing, making it more stable and efficient.



A diagram showing vortices formed by the alulea attaching airflow to the wing's upper surface.

Source: Sang-im Lee, Jooha Kim, Hyungmin Park, Piotr G. Jabłoński & Haecheon Choi on 07 May 2015, at
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4423427/
CC BY 4.0 DEED

Conclusion

My hypothesis was correct, as the added bird adaptations did substantially improve the wing's lift, lift-to-weight ratio, and stall angle. The lift produced by the wing with bird adaptations was consistently around 27% higher than the control wing, which means that the bird wing could create more lift than the control wing could at the same speed. In addition, the bird wing only stalled and lost lift at a 75° angle of attack, while the control wing stalled at 45°. Just before stalling, the bird wing generated a peak lift of 0.024N, while the control wing only reached 0.016N. This amount of high lift and stall angle is useful for short landings, where the aircraft has to create enough lift to support its weight, but also is moving very slowly at a high angle of attack.

Sources Of Error

Due to my limited equipment, my homemade data collection system in the wind tunnel was not very consistent. This could be because of small changes in slider position, and inaccuracies in scale reading. I also was unable to perform more trials of the stall angle tests, as they were very tedious and took a long time to complete, but given more time I would have performed more trials.

Extension

Right now, the alula wouldn't be suitable for high-speed aircraft, because of the air compression underneath the alula, which would make it very unstable. This could be solved by making the alula retractable, either manually or free-moving. The free-moving alula could work by usually being pressed down onto the wing by oncoming airflow, then being blown upwards when the wing reaches a certain angle of attack. I could also experiment with curving the wingtip, much like an elliptical wing, and adding differently sized and shaped wingtip slots, like those found in most elliptical winged birds. With access to more equipment, I would test high-speed wings, like those found on falcons, so this technology could be used for faster aircraft, but I don't have access to equipment to generate sufficiently high windspeeds right now.

Applications

Many aircraft could use this technology, especially those that require capabilities similar to those of birds. Gliders could use raptor-like wings, which provide them with low vortex-induced drag and high lift, which are important while gliding at low speeds. Another application of this technology is for short takeoff and landing aircraft, such as bush planes. Alulea could be used to prevent stalling and increase lift at low speeds and high angles of attack, which are useful for taking off and landing with minimal runway. Commercial aircraft could benefit from both the increased stall angle and the increased lift, but this wing is currently not adapted for the high windspeeds that commercial aircraft operate at, and would require many more modifications before being accepted into this market. When adopted, this technology could reduce runway lengths, and increase fuel efficiency with increased lift. Alulea, being an external addition to the wing, could quickly be adopted as a post-market device, which can be quickly installed on existing aircraft without many modifications.

Acknowledgments

Many people helped me along the way with this project. Just a few people I'd like to thank are:

- My parents, for supporting me through the whole project
- Ivan Phillipsen, for answering some of my questions about bird evolution.
- Paul Gies, for answering my questions about the applicability of this technology in the current aviation industry.
- Mrs.Secord-Tomlin and Mrs.Davis, for guiding me through this project from a judge's point of view.