How birds fly according to Newtonian physics.

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Independent Research

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Wings push air down; the reaction pushes the bird up.

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Fig 1a-i. Canadian goose. [69]

Abstract

A new explanation for the physics of how birds fly based on Newtonian mechanics is straightforward: In flight during the downstroke, birds' wings pass through a mass of static air (m), which is accelerated (a) diagonally downward and slightly backwards, to create a downward force ($Force_{DOWN}$ = ma). The reaction generates an equal and opposite force diagonally upward ($Force_{UP}$), which provides forward motion and vertical lift. See Fig. 1a-ii.

Simply put, the wings push air down and backwards, and the reaction pushes the bird forwards and up. The lift generated is analysed according to Newtonian mechanics based on: (i) the mass flow rate as (Lift = ma = m/dt * dv) well as (ii) the change in momentum (Lift = ma = d(mv)/dt) of the air displaced downwards. Both methods produce the same result.

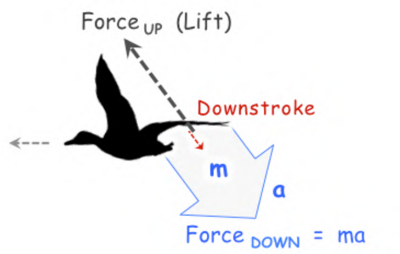

Fig 1a-ii. Newtonian mechanics.

This Newtonian approach is significant as it challenges the prevailing view that fluid mechanics and/or vortices explain how lift is generated by birds. It provides new and useful insights into lift that can enable better drones to be built, and allow biologists to better understand avian physiology. In addition, Newtonian mechanics offers a simple and easily understood explanation of lift that is consistent with accepted physics and what is observed in practice.

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1. Introduction

A. Why this research and analysis is significant.

The physics of how birds generate lift is of fundamental importance and is still debated. Currently, there is no conclusive experiment to prove any theory or equation for lift to be true. This novel Newtonian approach presented below challenges the prevailing theories of lift and provides:

- A simple and easily understood explanation of lift and flight that is consistent with accepted physics and what is observed in practice.
- A more accurate explanation of the physics of how birds fly as compared to other theories of lift (e.g. fluid mechanics, vortices, clap and fling, …).
- New insights to help biologists to better understand bird behaviour, wing movements, and physiology.
- New insights to enable better drones (UAVs) to be built.
- A better explanation of why hovering is inefficient.
- Highlights the importance of the Coanda effect on lift.
- An explanation of the physics of the empirical equations for lift as well as the kinetic energy required for lift. In turn, this allows the efficiency of lift generated by different birds to be compared.
- A universal theory of lift that applies to all objects that fly by pushing air down (airplanes, insects, ….).
- It is possible to verify or refute the Newtonian approach by experimentation by measuring the mass of air accelerate downwards and its velocity, and therefore, the lift generated by wings (Lift = ma).
- In contrast, theories of lift based on fluid mechanics (e.g. Navier-Stokes equations) and vortices do not accurately calculate lift, which helps to explain why the theory of lift is still unproven and debated.

*B. Lift = ma = m/dt * dv*

A more accurately calculation of the lift generated by a bird in a stable hover or forward flight uses the mass flow rate (m/dt), as explained below.

Wings with a positive AOA, pass through a mass of air each second (m/dt), which is accelerated to a velocity (dv) downwards, to create a downward force (Force $_{DOWN}$ = m/dt * dv).

The inertia of the air provides resistance to the downward force, generating a reactive equal and opposite upward force. Lift is the vertical component of the upward force, as shown by the equation: See Fig. 1b-(i-iii).

Force $_{DOWN}$ = ma = m/dt * dv
= Force $_{UP}$ (Lift)

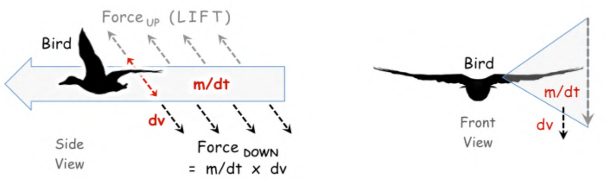

Fig. 1b-i. Newtonian forces acting on a bird's wing in **forward flight.**

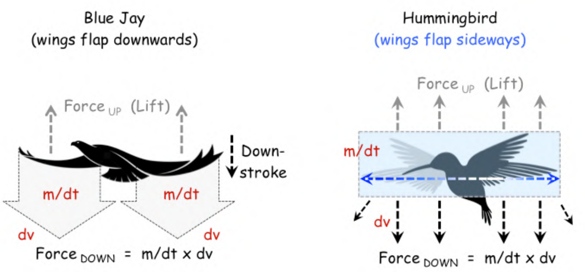

Fig. 1b-ii. Newtonian forces acting on a blue jay and hummingbird wings **hovering.**

Fig. 1b-iii. Airflows generated by a blue jay and hummingbird **hovering**.

The wings can push air downwards by moving vertically up-and-down like a blue-jay, or horizontally back-and-forth like a hummingbird; as long as a positive wing AOA is maintained.

To generate lift, momentum is transferred from the wings to the air, by accelerating the air downwards.

C. New analysis – The constant lift curve.

It is possible to analyse different combinations of 'm/dt' and 'dv' that generate sufficient lift to fly graphically, along a constant lift curve. See Fig. 1c-i.

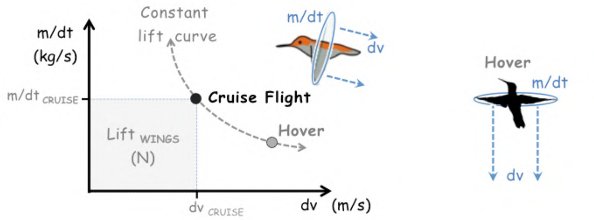

Fig. 1c-i. Lift composition – 'm/dt' and 'dv compared graphically.

The Newtonian methodology can be used to compare how lift is generated (Lift = /dt * dv) for different birds in forward flapping flight. For example, for each 1 kg of body mass of an albatross and hummingbird can be compared. See Fig. 1c-ii.

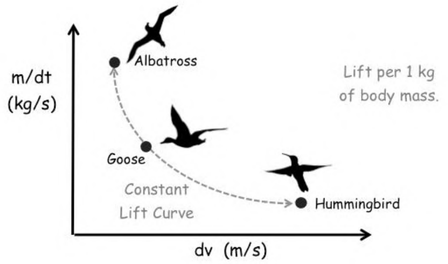

Fig. 1c-ii. Graph of lift generation by different birds, in forward flapping flight.

D. New analysis – The energy-efficiency of lift.

The same factors of mass (m) and velocity (v) of the air pushed downwards used to calculate lift (Lift = m/dt * dv), can be used to calculate the kinetic energy used to generate lift (K.E. = 0.5 mv^2) for different birds in flapping flight.

The energy-efficiency of lift of different birds can be compared to their wing aspect ratio and the amount of mass supported by each cm of wingspan. See Fig. 1d.

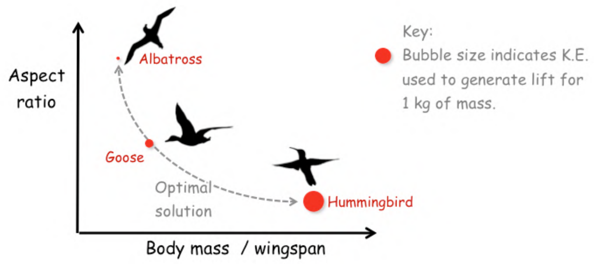

Fig. 1d. Graph of bird aspect ratio relative to bird mass / wingspan.

Contents:

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4. Newton Explains Lift

*A. Lift = m/dt * dv.*

Newtonian mechanics based on the mass flow rate (Lift = m/dt * dv) and a transfer of momentum is used to explain how lift is generated by a wing in passive soaring and active flight, using actual airflow analysis for birds.

The argument for Newtonian mechanics is presented below for each type of flight: See Fig 4a.

- Hovering.
- Normal flight.
- Gliding.
- Soaring.

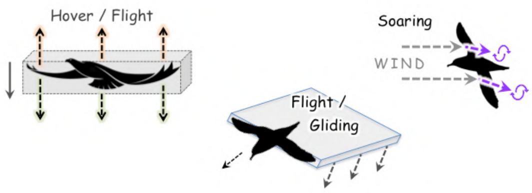

Fig. 4a. Different methods of generating lift.

Simply put, in a hover, flight, or glide the wings actively accelerate a mass of air each second (m/dt) to a velocity (dv) downwards. This action creates a force (Force $_{DOWN}$ = ma = m/dt * dv). The reaction causes the bird to be pushed upward. Momentum is transferred from the bird to the air to generate the force.

Soaring requires a different explanation. The wings passively re-direct a headwind (relative airflow) to decelerate (dv) a mass of air each second (m/dt) backwards. This action creates turbulence and a backwards force (Force $_{BACK}$ = ma = m/dt * dv). The reaction creates forward thrust, similar to how a boat sails into the wind. Momentum is transferred from the air to the bird to generate the thrust.

The wings can push air downwards by moving vertically up-and-down, or horizontally back-and-forth; as long as a positive wing AOA is maintained.

Abbreviations used:

- m = Mass of air flown through and pushed down.
- m/dt = Mass per unit time. Mass flow rate.
- dt = Change in time (per second).
- dv = Change in velocity (v) of the air displaced down.
- v = Velocity of the air displaced downwards.
- a = dv/dt = Acceleration.

Equations used:

- Force = ma = m * dv/dt = m/dt * dv [1]
- Force = ma = m * dv/dt = d(m/v)/dt [1]
- Momentum = mv [1]

B. Hovering.

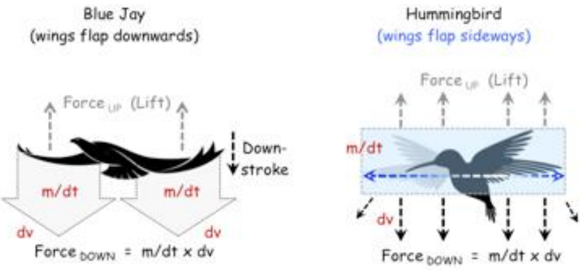

Fig. 4b-i. Newtonian forces acting on a bird hovering.

Fig. 4b-ii. Airflows generated by a blue jay and hummingbird hovering.

According to Newtonian mechanics, for a bird in a stable hover, the wings with a positive AOA, pass through a mass of air each second (m/dt), which is accelerated to a velocity (dv) downwards, to create a downward force, as described by the equation: See Fig. 4a-(i-ii).

$$Force_{DOWN} = ma = m/dt * dv \quad (1)$$

The inertia of the air provides resistance to the downward force. This dynamic allows for the generation of a reactive equal and opposite upward force:

$$Force_{DOWN} = Force_{UP} \ (Lift) \quad (2)$$

Lift is the vertical component of the upward force. Simply put, the wings push air down, causing the bird to be pushed up. If induced drag is negligible, then lift equals the upward force:

$$Force_{UP} = Lift \quad (3)$$

Then equations (1), (2), and (3) can be combined as follows:

$$Force_{DOWN} = Force_{UP} = Lift = m/dt * dv \quad (4)$$

Or simply: $$\mathbf{Lift = m/dt * dv} \quad \mathbf{(5)}$$

Units: $$N = kg/s * m/s$$

In each wing cycle, birds transfer momentum and kinetic energy from their wings to the air by accelerating the air downwards. See Fig. 4b-iii.

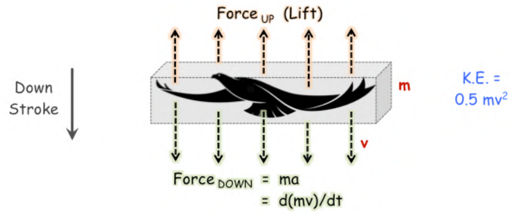

Fig. 4b-iii. Momentum transferred to the air in a hover.

There is no net gain or loss of momentum, energy and mass in this process of generating lift. In flight, wings transfer momentum and kinetic energy from the bird to the air, by accelerating the air flown through downwards to generate lift. The transfer of momentum and kinetic energy are expressed by the equations: See Fig. 4b-ii.

$$Force_{DOWN} = ma = d(mv)/dt \qquad (6)$$

$$K.E. = 0.5\ mv^2$$

Combining equations (2), (3) and (6) allows lift to be expressed as the change in momentum of the air:

$$Force_{DOWN} = Force_{UP} = Lift = d(mv)/dt \qquad (7)$$

$$\text{Or simply:} \quad Lift = d(mv/)dt \qquad (8)$$

Two Newtonian approaches to explain lift.

The analysis above provides two Newtonian methods and equations to calculate the lift generated by a wing:

$$Lift = ma = m/dt * dv \quad \text{(mass flow rate)} \qquad (5)$$

$$Lift = ma = d(mv)/dt \quad \text{(momentum theory)} \qquad (8)$$

Both lift equations (5) and (8) are based on Newtons 2nd Law of Motion (Force = ma). Both are correct and produce the same values, but express the same thing slightly differently.

Evidence of downwash – Wind tunnel experiments.

Evidence that birds push air down to fly is provided by wind tunnel experiments. For example, smoke blown over a hummingbird hovering in a wind tunnel show air being pushed downwards with each wing beat. Turbulent airflow arises behind the hummingbird, on the leeward side. See Fig. 4b-iv.

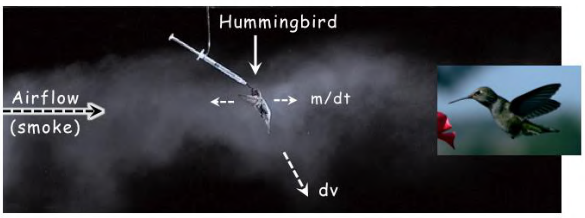

Fig. 4b-iv. Hummingbird hovering in a wind tunnel. [61][65]

Evidence of downwash – Other research

Various research supports the assertion that birds and other animals push air downwards in flight to create downwash:

- The wake structure measured below the birds' (flycatchers) results in a relatively high downwash behind the body. Analysis of birds flying in wind tunnels showed uniformly distributed spanwise downwash. [84]
- Hummingbird wings generated a mean downward velocity of 1.1 m/s. [83]
- "We show how the air behind the body of a long-eared bat accelerates downwards, ..." [82]

However, the research did not directly attribute downwash to the lift generated, based on Newtonian mechanics. Often research correlates downwash with wingtip vortices.

Factors that affect 'm/dt' and 'dv'

'dv' depends primarily on aircraft momentum (airspeed and mass), wing AOA, and wing depth (chord).

'm/dt' depends on the volume of air flown through and air density. The volume of air flown through depends on wing cycle frequency, and the volume of air displaced on each wing beat. In turn, the volume of air displaced on each wing beat depends on wing shape, wingspan, wing depth (chord) and vertical wing reach (distance). See Fig. 4b-(v-vi).

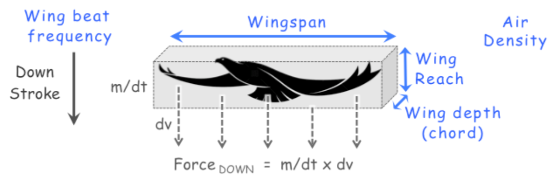

Fig. 4b-v. Factors that affect 'm/dt' and 'dv', for a bird flapping its wings in the vertical direction.

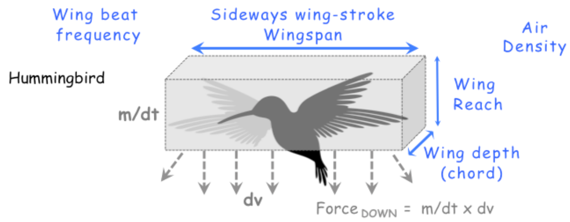

Fig. 4b-vi. Factors that affect 'm/dt' and 'dv', for a bird flapping its wings sideways.

Change in time (dt)

The thin layer of air flown through by the wings is time-dependent, and therefore, is expressed as the mass flow rate 'm/dt', and not just 'm'. i.e. The mass of air displaced by the wing increases with airspeed or wing beat frequency; which are time-dependent.

The change in velocity of the air flown through and pushed downward is expressed as 'dv'. It is not expressed as acceleration 'dv/dt', because this action is due to a one-off force (impulse) from the wings against the air. This force is not continuously applied to the same mass of air (e.g. air molecules), and therefore, it is not time-dependent.

Two airflows

There are two airflows in passive and active force generation. The underside of the wings physically push or re-direct the air under the wing. A vacuum of low air pressure on the topside of the wing pulls (sucks) or re-directs the air above it downwards, helped by the Coanda effect.

7. Wing Airflows

A. *Two wing airflows.*

In flight, there are two separate airflows evident on the wings:

(i) The underside of the bird's wing directly pushes air down. This causes high air pressure under the wing; due to the force applied directly by the wing (i.e. Pressure = Force / Area).

(ii) The curved topside of the bird's wing pulls air downwards due to a vacuum (low air pressure) created above the wing, as the wing moves downwards. The Coanda effect can significantly enhance the mass of air displaced down. See the explanation of the Coanda effect in the next section. See Fig. 7a-(i-ii).

Fig. 7a-i. The bird's wings push and pull air down.

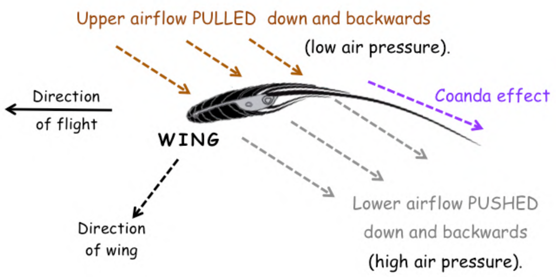

Fig. 7a-ii. Wing cross-section on the downstroke.

Birds flying head-on into the wind have a relatively low AOA. This provides minimum resistance to the direction of flight. The wings move and change shape during the wing cycle. Therefore, the wing AOA varies during the wing cycle. See Fig. 7a-iii.

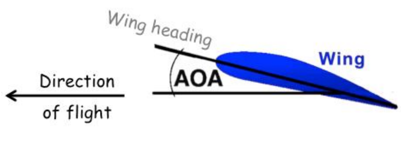

Fig. 7a-iii. Wing angle of attack (AOA).

B. *The Coanda effect and laminar airflows.*

Fluid flow naturally follows a curved surface due to the Coanda effect.

For example, water falling from a tap is passively re-directed to the right (and slightly up) by the curved side of a spoon due to the Coanda effect. According to Newtonian mechanics, this action creates a small turning force, due to the change in momentum of the water flow. The reactive equal and opposite force pushes the spoon sideways to the left (and slightly downwards). See Fig. 7b-i.

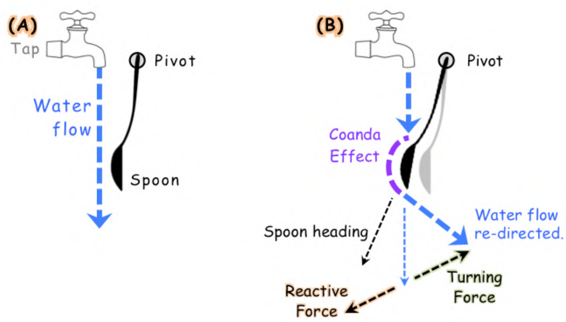

Fig. 7b-i. Spoon experiment demonstrating the Coanda effect.

Wind tunnel experiments

Wind tunnel experiments demonstrate airflows arising due to the Coanda effect on the topside of a curved airplane wing, as well as the turbulence that arises on a flat wing. See Fig. 7b-ii.

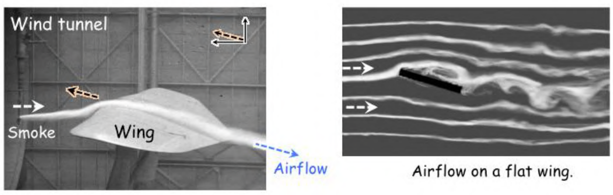

Fig. 7b-ii. Airflow on curved and flat wings. [79][81]

In general, wings produce a stronger Coanda effect with laminar (smooth / non-turbulent) airflow at a lower AOA, higher airspeed, and where the wings are deepest (largest chord, such as near the fuselage). Conversely, the Coanda effect is weakest at high AOA, slower airspeeds, and where the wings are narrow (small chord, such as at the wing tips). The flat undersides of wings are typically designed to push air down without inducing any Coanda effect. See Fig. 7b-iii.

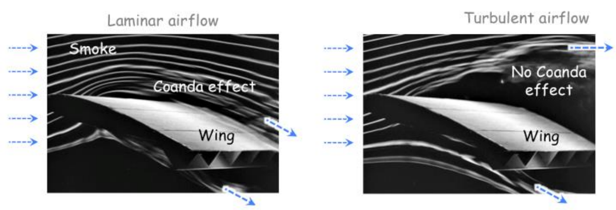

Fig. 7b-iii. Smooth vs. turbulent airflows on a wing. [80]

C. Addendum: Airplane wings' actual wing airflows.

Airplane wings are used as a proxy to demonstrate analysis of the actual wing airflows that actively generate a force, as described below. This approach differs to analysis of relative wing airflows that passively generate a force.

The topside and underside of a wing with a positive AOA, accelerates the static air flown through downwards and slightly forwards, creating two separate airflows. See Fig. 7c-(i-ii).

1) The **underside** of the wing directly exerts a force against the air flown through that **pushes** the air downward.

2) Low pressure on the **topside** of the wing indirectly **pulls** air down, helped by the Coanda effect and gravity.

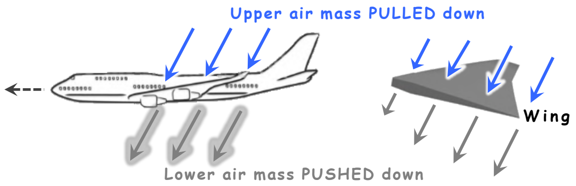

Fig. 7c-i. Two actual airflows on a wing.

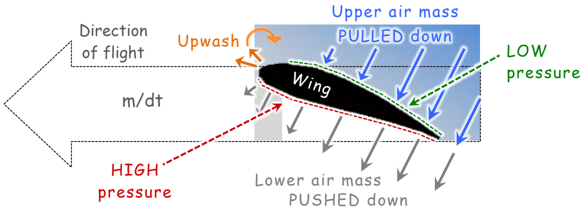

Fig. 7c-ii. 2D diagram of actual wing airflows.

The wing airflows generated can be illustrated by the path of air molecules above and below the wing. See Fig. 7c-iii.

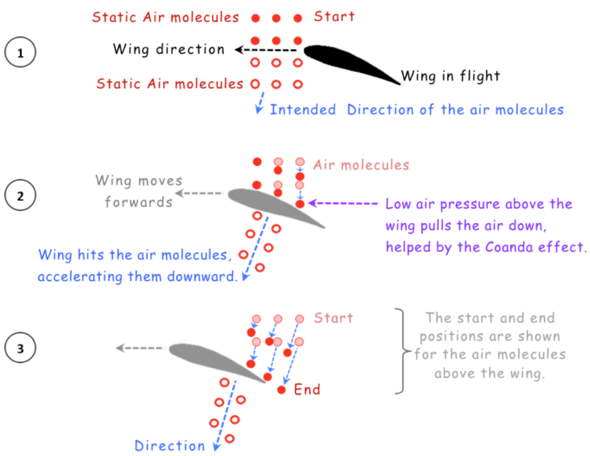

Fig. 7c-iii. Actual path of air molecules as the wing moves forwards in flight.

The two wing airflows are described in more detail below:

1) The **underside** of the wing directly **pushes** air down. See Fig. 7c-iv.

   The force exerted by the wing on the air creates high pressure on the underside surface of the wing, as described by the equation for pressure (Pressure = Force /Area).

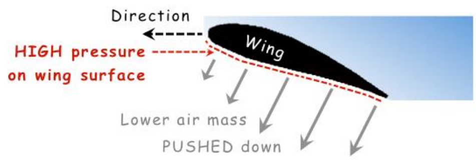

Fig. 7c-iv. The underside of the wing directly pushes air down.

2) The forward movement of the wing creates a zone of low pressure (vacuum) behind it on the **topside** of the wing. See Fig. 7c-v.

   The low pressure zone indirectly **pulls** air above the wing downwards, helped by:

   - Any wing curvature due to the Coanda effect.
   - The weight of the atmosphere (i.e. gravity) pulls the air above the wing downwards, into the area of low pressure on top of the wing created by the forward movement of the wing.

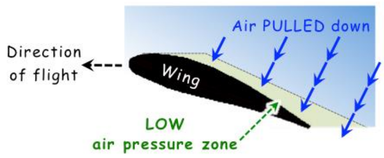

Fig. 7c-v. The topside of the wing indirectly pulls air down.

Additional considerations include:

- The leading edge of the wing initially pushes the air up and forwards, creating upwash.
- If the air above the wing pulled down does not reach the trailing edge of the wing by the time that the wing has moved forwards. Then turbulence can arise, triggering airflow separation and a **stall**. This dynamic explains why stall arise at the trailing edge of the wing.
- After the wing has passed forwards, the lower and upper air masses accelerated by the wing continue to descend due to the momentum gained.
- The generation of lift produces a **pressure difference on the wing**; Low pressure on the topside of the wing and high pressure on the underside of the wing.

  Contrary to the prevailing view, this paper argues that wing the pressure patterns observed are a **consequence** of the airflows and resultant process that generates lift, and **not a direct cause** of lift.

  As the airflows have been accelerated, they both have low internal air pressure.

18. Discussion of Results

The Newtonian approach is significant as it provides new and useful insight, which are not available from other theories of lift and flight, including fluid mechanics.

This analysis helps to resolve the debate regarding the physics of lift between Newtonian and fluid mechanics.

- It should not be surprising that Newtons Laws of Motion can explain the physics of how lift is generated. It would be more surprising to claim the reverse, that Newtonian mechanics cannot explain lift (as claimed by advocates of fluid mechanics).
- It should be possible to perform calculations that confirm or refute whether Newtonian physics explains how birds fly; And whether birds hovering to displace a mass of air downwards each second, equal to its mass, to achieve buoyancy.
- Furthermore, it is puzzling that this Newtonian approach has not been proposed previously.
- The analysis in this paper is similar to that provided in the paper 'Newtons laws explain insect flight.' [15]

Newtonian physics provides a method to resolve the debate for how birds fly in flapping flight.

19. Conclusions

Newtonian mechanics based on the mass flow rate explains how birds generate lift (Lift = m/dt * dv). See Fig. 18a.

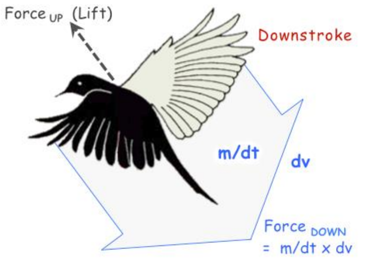

Fig. 18a. Newtonian forces acting on a bird in flight.

Newtonian mechanics provides a simple explanation for lift consistent with what is observed in practice and accepted physics. As a wing circulates the air in flight, momentum is transferred from the wings to the air.

20. Additional Information

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Personal background: The author is British, currently living in France, and was born in 1966 in Botswana. The author is dyslexic. The author held a private pilot's license (PPL) for 18 years. He flew and maintained a small, single-engine, home-built airplane (Europa XS monowheel, registration: G-OSJN).

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Professional background: The author qualified as an accountant (ACA) in England & Wales, as well as a Chartered Financial Analyst (CFA). He worked in finance for 24 years in numerous countries for different companies.

Author Contributions: This paper is entirely the work of the author, Mr. Nicholas Landell-Mills.

Affiliations: None.

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Project costs: The direct expenses used to write this paper were minimal and included things like a computer, internet access, and living expenses. However, the opportunity cost of the salary forgone by not being employed while conducting the research for over eight years, was substantial.

Request for financial support: This paper could not have been produced through the established academic and scientific systems. There is no intention to publish this paper or its contents in an academic journal, as then it would no longer be available for free to all. If you found this research to be useful, valuable, informative, entertaining, or otherwise worthy. Then kindly thank, support, and encourage the author with a financial donation via:

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- Or buy me a coffee: https://bmc.link/zhJIg4zRCW

Thank you!