How boomerangs fly according to Newtonian mechanics.

Preprint · December 2019

1 author:

Nicholas Landell-Mills
Indigo

How boomerangs fly according to Newtonian mechanics.

Mr. Nicholas Landell-Mills

30 May 2022
Pre-Print DOI: 10.13140/RG.2.2.12719.48806;

Keywords: Aerodynamics; boomerang, lift; Newton; physics;

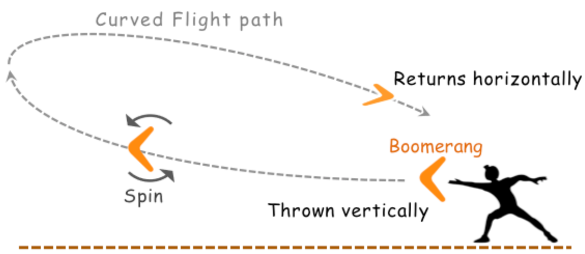


Fig. 1a. Boomerang's curved flight path.

Abstract

It remains unproven how a boomerang generates lift, and more importantly, how it achieves a curved path through the air, if thrown correctly. The boomerang is thrown vertically, but return flying flat (horizontally). See Fig. 1a. A number of hypotheses have been proposed, but none have been proven by experimentation and none rely on Newtonian mechanics.

In flight, the air flown through is pushed downward and sideways by the boomerang. The equal and opposite reactive force (thrust) pushes the boomerang upwards against gravity and sideways in a curved flight path back to its starting point.

The enigma of the curved flight path is explained by the boomerang's AOA, which creates a force almost perpendicular and slightly backwards to the boomerang's direction of travel. The uneven nature of the curved flight path is explained by the changing AOA as the boomerang's speed slows. The curved flight path is not by explained spin, torque, or angular momentum as commonly believed. See Fig. 1b.

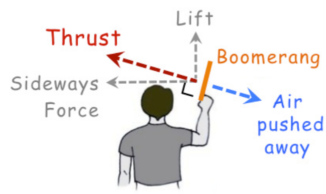


Fig. 1b. Thrust generation. [37]

I. Introduction

A. Newtonian mechanics.

A boomerang has a wing-like design with a thick leading edge and a tapered trailing edge provides it with a positive angle of attack (AOA). See Fig. 1c.

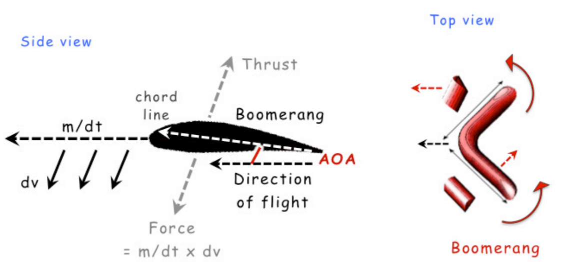


Fig. 1c. Newtonian forces acting on a boomerang (cross-section).

According to Newtonian mechanics, a boomerang in flight flies through a static mass of air each second (m/dt) that it accelerates to a velocity (dv) away from the boomerang at a near perpendicular direction, helped by the Coanda effect. This action creates a force (Force = ma = m/dt * dv).

The reaction generates an equal and opposite force (Thrust = m/dt * dv). Thrust generates lift and a sideways force. Due to the boomerang's AOA, some thrust is directed slightly backwards, causing the boomerang's curved path.

In contrast, a helicopter rotor blade (or propeller) cannot achieve a curved path because the twist in its blades provides an AOA perpendicular to the blade orientation (spin). See Fig. 1d.

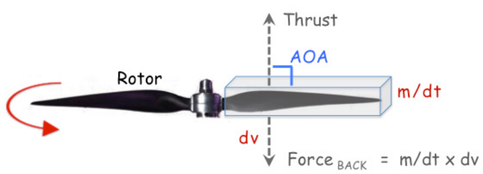


Fig. 1d. Newtonian forces acting on a rotor.

In the absence of the twist in the helicopter's rotor blades, the rotors could create forces for the helicopter to achieve a curved flight path similar to a boomerang. However, this would be undesirable.

Boomerang AOA and flight path

The difference in the angles of the AOA across the boomerang's arms is sufficient to produce a net backward angle for the thrust generated. This aspect then determines the boomerang's curved flight path. See Fig. 1e.

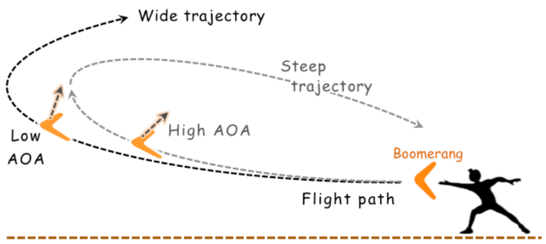


Fig. 1e. Boomerang flight paths depend on the AOA.

The AOA depends on factors such as the boomerangs shape, spinning (rotational) speed, and true forward airspeed.

B. Significance.

This novel analysis is significant as it provides a simple explanation of how boomerangs fly to a select group of disc enthusiasts that is consistent with accepted physics and what is observed in practice. This analysis means that the best performing boomerang maximizes the Coanda effect on the topside of the boomerang. However, a lack of reliable data means that it is difficult to establish the true explanation for how boomerangs fly.

Attempting to solve the enigma of a boomerang's curved flight path and lift generation, it is noteworthy that the theory of how airplanes fly is also still unresolved (see Appendix I).

Contents

II. BACKGROUND

A. Standard forces.

The standard forces acting on a boomerang include two pairs of equal and opposite forces: thrust & drag; lift & weight. See Fig. 2a.

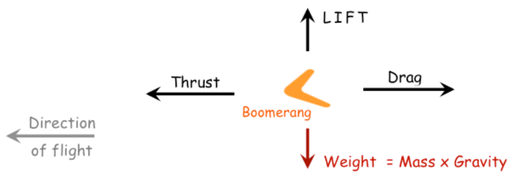


Fig. 2a. Standard forces acting on a boomerang.

B. Basic features.

The basic boomerang features are shown in Fig. 2b-i.

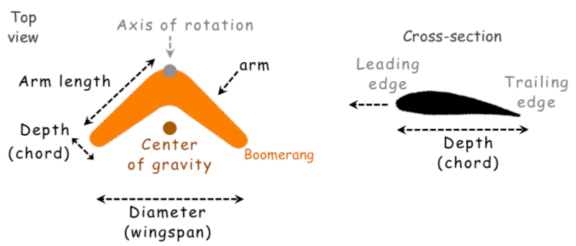


Fig. 2b-i. Basic features of a boomerang.

Boomerangs come in a variety of shapes, designs and sizes. The basis design involves arms extended from a central point, around which it spins when thrown. The physics is the same for all types of boomerangs. These shapes allow boomerangs to maintain a stable spin (rotation around their axis). in flight, similar to a frisbee. See Fig. 2b-ii.

Fig. 2b-ii. Types of boomerangs.

C. Shape and design.

Frisbees, flying rings, and boomerangs have the same basic shape, design and function as airplane wings, helicopter rotors, and propellers. They have a relatively thick leading edge facing the direction of travel, as well as a thin trailing edge. Only frisbees lack a thin trailing edge, as they spin on their center of gravity. The basic aerodynamics and forces acting on them are the same. See Fig. 2c-i.

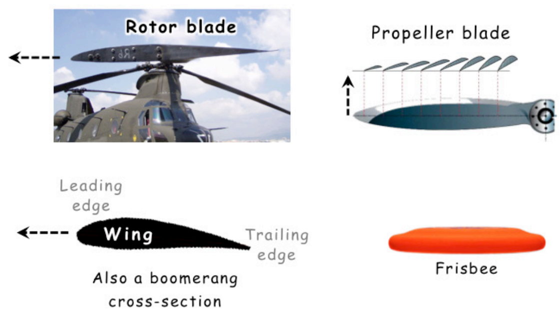


Fig. 2c-i. Rotor, wing, frisbee, wing and propeller design.

The leading edge appears on alternate edges of the boomerang, to face the direction of travel as it spins. See Fig. 2c-ii.

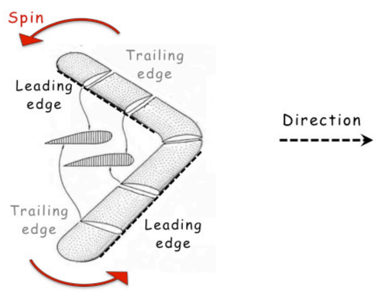


Fig. 2c-ii. Design of a boomerang. [47]

D. Angle-of-attack (AOA).

The boomerang's AOA depends on its heading relative to its chord line. See Fig. 2d.

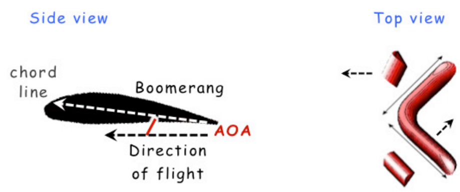


Fig. 2d. Boomerang AOA.

III. Newton Explains Thrust

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

Where:
- m = Mass of air flown through and pushed down.
- m/dt = 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 down.
- a = dv/dt = Acceleration.
- Force = ma = m * dv/dt = m/dt * dv [1]
- Force = ma = m * dv/dt = d(m/v)/dt [1]
- Momentum = mv [1]

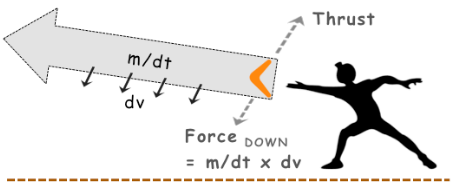


Fig. 3a- Newtonian forces acting on a boomerang.

The same principles of physics of how airplane wings, propellers and frisbees fly by actively generating a force, can be applied to explain how boomerangs fly.

Simply put, the boomerang pushes air as it flies spinning forwards, The reactive force from the spin (thrust) pushes the boomerang sideways to adopt a curved path, and upwards – if thrown correctly. See Fig. 3a.

According to Newtonian mechanics based on the mass flow rate, for a boomerang in stable flight through static air, which has a positive angle of attack (AOA). The boomerang flies through a mass of air each second (m/dt), which it accelerates to a velocity (dv) away from it. This action crates a force: as described by the equation:

$$\text{Force}_{\text{AWAY}} = ma = m/dt * dv \qquad (1)$$

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

$$\text{Force}_{\text{AWAY}} = \text{Thrust} \qquad (2)$$

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

$$\text{Force}_{AWAY} = \text{Thrust} = m/dt * dv \qquad (3)$$

$$\text{Or simply:} \quad \text{Thrust} = m/dt * dv \qquad (4)$$

$$\text{Units:} \quad N = kg/s * m/s$$

The values for 'm/dt' and 'dv', and therefore thrust (Thrust = m/dt * dv), depend on a number of factors such as: the AOA, flight and rotation speeds, diameter (wingspan), wing depth (chord), thickness (wing reach), and boomerang momentum.

In these equations above the increased velocity of the air is expressed as 'dv', and not as acceleration ('dv/dt'), because this action is not time dependent. It is due to a one-off force (impulse) from the boomerang. In contrast, the mass of air flown through by the boomerang is time dependent, and therefore, is expressed as the mass flow rate (m/dt).

This Newtonian explanation of thrust (Thrust = m/dt * dv), is consistent with the standard equation for kinetic energy (K.E.= 0.5 mv^2). Both are based on a small mass of air being accelerated to a velocity. See Fig. 3a.

The mass of air flown through each second by the boomerang (m/dt) depends on the volume of air flown through and air density. In turn, the volume of air flown through each second depends on boomerang airspeed, diameter (wingspan), and thickness. See Fig. 3a-iii.

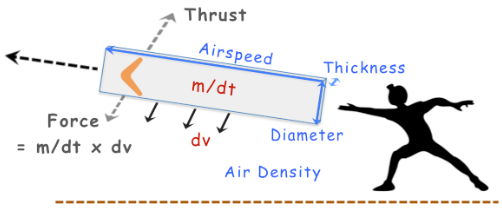


Fig. 3a-iii. Mass of air flown through each second (m/dt).

B. *The momentum theory of lift.*

There is no net gain or loss of momentum, energy and mass in this process of generating thrust. In flight, boomerangs transfer momentum and kinetic energy to the air. A key point is that the momentum of the boomerang affects how much momentum is available to be transferred to the air. A boomerang that lacks mass or velocity may not have sufficient momentum to transfer to the air to fly very far.

The force created by the transfer of momentum is expressed as the equation: See Fig. 3b.

$$\text{Force}_{AWAY} = ma = d(mv)/dt \qquad (5)$$

Combining equations (1) and (5) allows thrust to be expressed as the change in momentum of the air:

$$\text{Force}_{AWAY} = \text{Thrust} = d(mv)/dt \qquad (6)$$

$$\text{Or simply:} \quad \text{Thrust} = d(mv)/dt \qquad (7)$$

$$\text{Units:} \quad N = (kg * m/s)/s$$

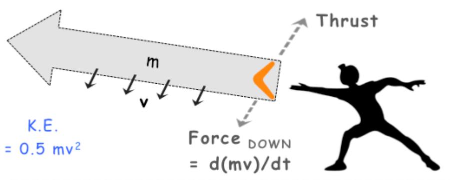


Fig. 3b. Transfer of momentum to the air.

C. *Two Newtonian equations for lift.*

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

$$Thrust = ma = m/dt * dv \qquad (mass\ flow\ rate) \qquad (4)$$

$$Thrust = ma = d(mv)/dt \qquad (momentum\ theory) \qquad (7)$$

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.

This explanation is similar to how frisbees fly according to Newtonian mechanics. See Appendix III. [10]

D. *Key forces acting on a boomerang.*

The thrust from the throw is the only source of force and energy that pushes the boomerang forwards (airspeed) and up (lift), as expressed by the equations: See Fig. 3d-i.

$$Thrust = \underset{(airspeed)}{Force_{FORWARD}} + \underset{(Lift)}{Force_{UP}}$$

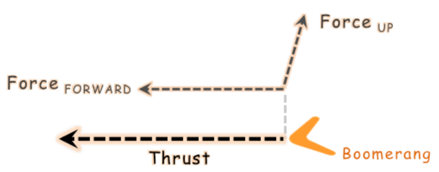


Fig. 3d-i. Engine Thrust = Force $_{FORWARD}$ + Force $_{UP}$

The forward force (Force $_{FORWARD}$) is the portion of thrust that propels the boomerang ahead.

The upward force (Force $_{UP}$) is the portion of thrust that pushes the boomerang upwards, which is generated from the forward force by pushing air downwards. Specifically, the boomerang with a positive AOA (helped by its curved topside) re-directs some thrust downward, by pushing air flown through down and slightly forwards to create downwash.

This action creates a downward force (Force $_{DOWN}$ = ma = m/dt * dv). The reactive equal and opposite upward force can be split between the two perpendicular vectors: lift and induced drag, as summarized by the equation: See Fig. 3d-ii.

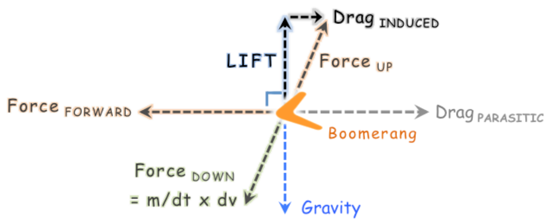


Fig. 3d-ii. Key forces acting on an boomerang.

Force $_{UP}$ = Lift + Drag $_{INDUCED}$

- Lift is simply the vertical part of the upward force.
- Induced drag is the horizontal and backward component of the upward force. If induced drag is negligible, then lift equals the upward force.

To accelerate the air downwards, momentum is transferred from the aircraft to the air. This means that the aircraft trades lower airspeed for lift (altitude).

In addition: the other key forces on an boomerang includes:

- Gravity pulls the boomerang downward.
- Parasitic Drag is the equal and opposite force to the forward force, which arises as the boomerang fuselage physically pushes the air in its path out of the way.

E. *The upward force (Thrust).*

The angle that downwash is pushed down determines how the upward force is split between lift and induced drag.

The boomerang's AOA depends on factors such as the curvature along its topside and its airspeed. Similar to propeller blades, adding the correct amount of twist in the boomerangs shape can provide an even AOA along the length of the arm.

Using trigonometry and the dynamics of a right-angled triangle (Pythagoras formula), it is possible to calculate lift and induced drag generated by the upward force. The angle (X°) that the wing pushes air downwards relative to the vertical, is the same as the angle (X°) that the upward force acts relative to the vertical. See Fig. 3e.

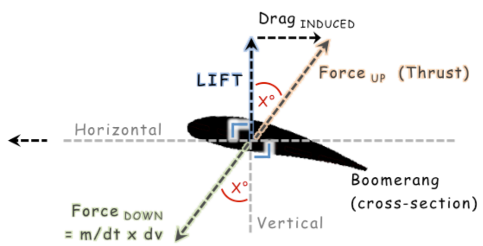


Fig. 3e. Trigonometry of the forces acting on a boomerang.

In this situation the Force $_{UP}$ is the hypotenuse of the right-angled triangle. Therefore, the forces can be split as follows:

$$Lift = Force_{UP} * Cos\,(X°)$$

$$Drag_{INDUCED} = Force_{UP} * Sin\,(X°)$$

If induced drag is not negligible as assumed above, then a more accurate equation for lift is not Lift = m/dt * dv, but:

$$\begin{aligned} Lift &= Force_{UP} * Cos\,(X°) \\ &= (m/dt * dv) * Cos\,(X°) \end{aligned}$$

F. AOA and angle of the upward force (Thrust).

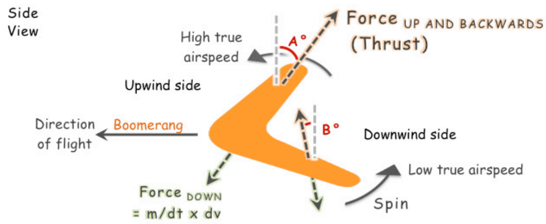


Fig. 3f-i. Different angles on the upward forces.

The upwind and downwind arms the boomerang experience different AOA and angle on the upward force (thrust), as they have different true (ground) airspeeds. Overall, the net effect produces a greater lift and a backward AOA on the upwind side of the boomerang: See Fig. 3f-i.

- The arm of the boomerang facing the direction of travel, (upwind side), has the highest true airspeed, as the arm is rotating in the same direction that the boomerang is moving. The high airspeed produces greater lift, AOA, and backward angle of the upward force (A°), on the upwind side.

  The higher relative airspeed on the upwind side increases the lift generated (Lift = m/dt * dv), as the arm flies through a greater mass of air each second (higher m/dt), as compared to the downwind arm.

- In contrast, on the downwind side the arm has the slowest true airspeed. This produces the lowest: lift, AOA, and backward angle of the upward force (B°).

Boomerang 2D lift distribution

The Lift distribution across the boomerang is uneven. Little lift is generated in the center, where the boomerang's spin (angular momentum) is lowest. In addition, the AOA varies across the boomerang, as described above. The boomerang's center of gravity at the mid-point. Therefore, the lift distribution across the boomerang is uneven, making the boomerang unbalanced. See Fig. 3f-ii.

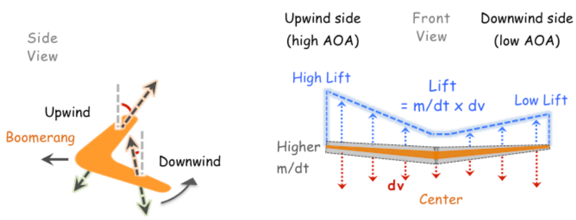


Fig. 3f-ii. 2D lift distribution across a boomerang.

Due to a lack of experimental results, these aspects have not been quantified accurately yet. However, the logic above is similar to an adverse yaw experienced on an airplane in a bank. See Appendix IV.

G. AOA and flight path.

The difference in the angles of the AOA across the boomerang's arms is sufficient to produce a net backward angle for the thrust generated. This aspect is the key element that determines the boomerang's curved flight path. However, a lack of experimental evidence means that this assertion is not conclusively proven. See Fig. 3g-i.

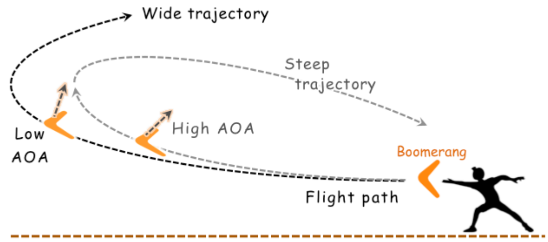


Fig. 3g-i. Boomerang flight paths depend on the AOA.

To put it another way, the boomerang's AOA determines the induced drag generated and the angle of the upward force. These factors then determine the curvature of the boomerang's flight path.

- An overall lower net AOA creates less induced drag and a more vertical upward force. This dynamic provides a lower curvature to the boomerang's trajectory.

- An overall higher net AOA creates more induced drag and a less vertical upward force. This dynamic provides greater curvature to the boomerang's trajectory.

  The high AOA configuration is less efficient at generating lift due to the greater induced drag, as compared to the low AOA.

Boomerangs produce an uneven curved flight path as the relationships between airspeed, rotational speed and AOA are non-liner. In addition, the decline in airspeed over the flight path is non-linear as drag is proportional to airspeed squared.

Boomerang spin rate and flight path

The spin speed of the boomerang significantly exceeds the forward true airspeed of the boomerang. This aspect allows the AOA to vary significantly across the boomerang. This means that, the faster that the boomerang spins, the greater that the AOA will vary across the boomerang. Therefore, the greater the boomerang's curvature in its flight path. See Fig. 3g-ii.

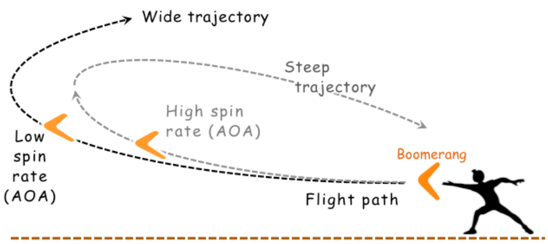


Fig. 3g-ii. Flight paths depend on the boomerang's spin rate, and therefore, the AOA.

H. Absolute airflows.

In terms of airflows, the underside of the boomerang pushes the air down. Whereas a vacuum of low air pressure on the topside of the boomerang pulls air down, helped by the Coanda effect. This is similar to the airflows observed on an airplane wing. See Fig. 3h-i.

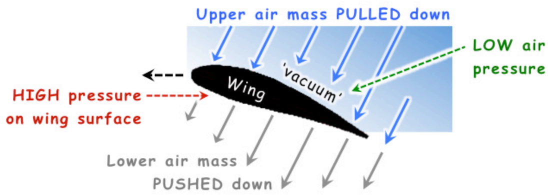


Fig. 3h-i. 2D diagram of wing airflows.

The two separate airflows are summarized:

1) **The underside of a boomerang** physically pushes the air flown through below it downwards and slightly forwards. This creates high pressure on the underside surface of the boomerang, based on the standard equation for pressure (Pressure = Force /Area [1]). See Fig. 3h-ii.

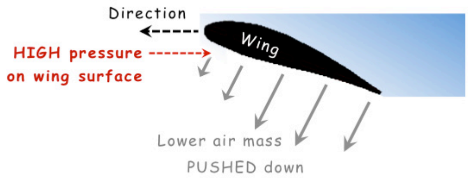


Fig. 3h-ii. Underside of the boomerang pushes air down

2) **On the topside of the boomerang** a zone of low air pressure arises, due to the forward movement of the boomerang creating a relative vacuum (void) behind it. See Fig. 3h-iii.

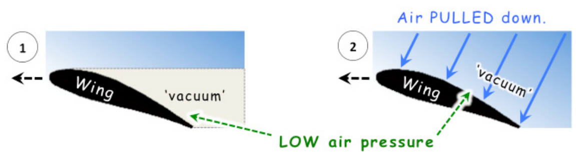


Fig. 3h-iii. Vacuum behind the topside of the boomerang.

The atmosphere above the boomerang pushes the upper air mass downwards towards the top of the boomerang, helped by gravity. Also, the low air pressure pulls the air above the boomerang downwards. After the boomerang has passed, the upper air mass continues to descend.

See Appendix II for a more detailed explanation.

Relative vs. Absolute airflow analysis

The Newtonian approach to lift is based on absolute airflow analysis, as compared to the conventional approach that focuses on relative airflows. See Fig. 3h-iv.

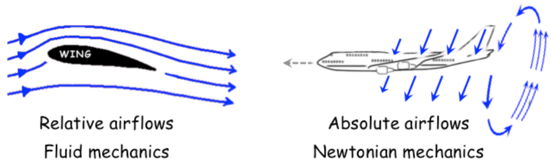


Fig. 3h-iv. Relative vs. Absolute airflow diagrams for an airplane wing.

I. Propellers and adverse yaw.

The Newtonian explanation of a boomerang's curved flight path is consistent with the Newtonian explanation of propeller forces (P-Factor) and the adverse yaw experienced on airplanes banking. See Appendix IV.

In short, asymmetric propeller loading, or a 'P-Factor' can arise on a single engine airplane on take-off, at high power and high wing AOA, to yaw to the left. The left yaw is caused by a change in the propeller AOA See Fig. 3i-i.

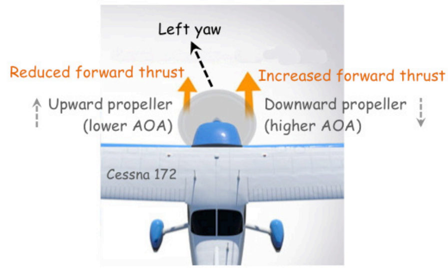


Fig. 3i-i. P-Factor and left yaw. [46]

Similarly, an adverse yaw experienced on an airplane banking is also caused by a variation in wing AOA. See Fig. 3i-ii.

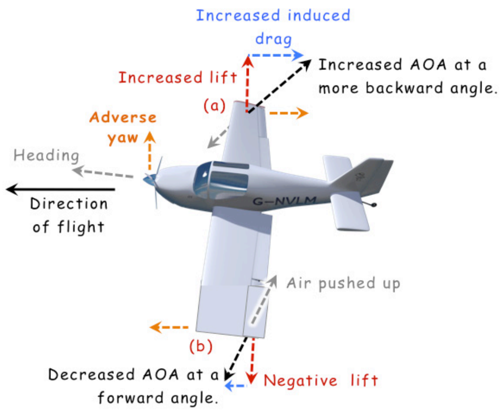


Fig. 3i-ii. Forces acting on an airplane in a bank.

IV. More on the Flight Path

A. Boomerang path when thrown horizontally.

Evidence that boomerangs generate thrust in flight perpendicular and slightly backwards to the plane of spinning; is provided by boomerang's flight path if thrown flat (horizontally). See Fig. 4a-i.

Fig. 4a-i. Thrust generated by a boomerang. [42]

Once the boomerang is flying vertically it quickly loses speed and momentum. This reduced the AOA and the rate at which the boomerang turns. This dynamic limits the boomerang's capacity to complete a loop while in flight.

Similar to an airplane wing, the boomerang requires a small positive AOA to generate thrust, which means that the trust is generated at a slightly backwards angle. See Fig. 4a-ii.

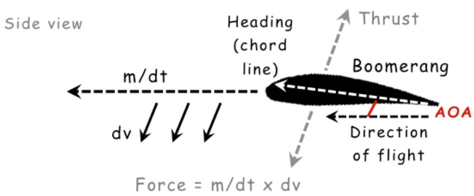


Fig. 4a-ii. Cross-section view of the forces on a boomerang.

The curvature of the boomerang means that even a flat boomerang can have a positive AOA, similar to an airplane wing.

When thrown horizontally, the positive AOA causes the boomerang to turn upwards. The thrust generated is pulling the nose of the boomerang upwards. This aspect can also be shown via the diagram in Fig. 4a-iii.

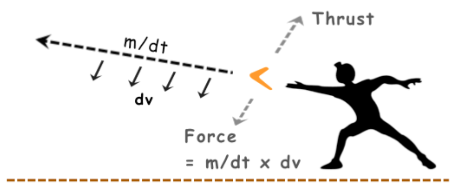


Fig. 4a-iii. Thrust acting on a boomerang thrown horizontally.

B. Boomerang path when thrown vertically.

The boomerang AOA described above also explains the curved path of a boomerang back to the original position, when thrown vertically. See Fig. 4b.

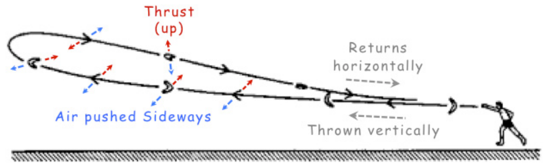


Fig. 4b. Boomerang flight path if thrown vertically. 1 [42]

Key features of the flight path include:

- The boomerang has to be thrown with adequate force and AOA in order to return to its original position.
- The boomerang is thrown at a near vertical orientation and lands with a flat (horizontal) orientation. This means that:
  - Initially much of the thrust generated is used to turn the boomerang. This dynamic explains why a boomerang initially can turn at the steepest angle of its flight.
  - Towards the end of the flight path, when the boomerang is flying horizontally, most of the thrust generated is used to push the boomerang up (lift).
- The boomerang does not follow a perfectly circular path, as its AOA changes with its airspeed. In addition, as the vertical angle of the boomerang reduces in flight, a declining proportion of the thrust generated is used to turn the boomerang.
- The angle of turn is steepest initially, and then slowly declines.
- The boomerang reaches it maximum altitude at approximately the mid-point of the flight. This trajectory slows the boomerang in the first half of the flight as it gains altitude; and accelerates the boomerang as it descends during the second half of the flight.
- Different flight paths depend on boomerang design and how it is thrown.

A boomerang performance is extremely sensitive to its AOA, because the arms of the boomerang are spinning. A small change in AOA can have a significant change in performance, as compared to a frisbee. For example, a boomerang can fly at a high AOA, whereas a frisbee can.

C. Additional images.

Additional images of the boomerang's flight path if thrown vertically are provided below. See Fig. 4c-i, and 4c-ii.

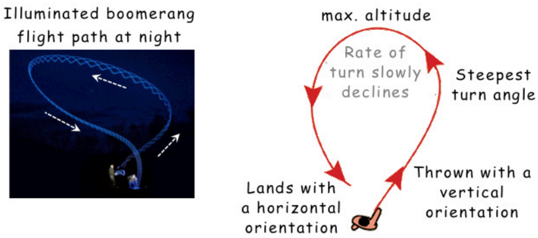


Fig. 4c-i. Boomerang flight path . [41] [38]

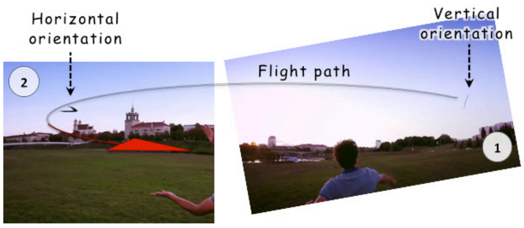


Fig. 4c-ii. Boomerang flight path 3. [37]

D. Boomerang release angle when thrown vertically.

A boomerang thrown initially in a near vertical angle (of about 15°) initially generates a force that is mostly directed sideways. Only a small proportion of the force is direct upwards for lift. See Fig. 4d-i.

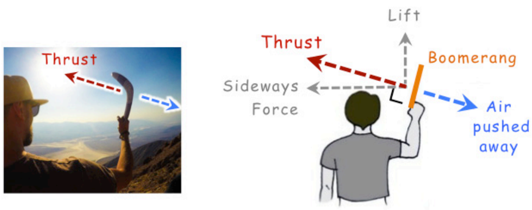


Fig. 4d-i. Forces acting on a boomerang. [37]

Specifically, according to the mathematics of a right angled triangle, if a boomerang is thrown at 15°, then only about 26% of the force generated is directed vertically upwards for lift. i.e. Cos (75°) = 0.2588. See Fig. 4d-ii.

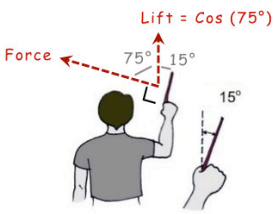


Fig. 4d-ii. Forces acting on a boomerang at 15°. [37]

E. Frisbee as a boomerang.

A frisbee can be thrown to replicate a boomerang's curved flight back to its starting position. A frisbee thrown upwards at a very high angle, slows as it gain altitude. It eventually slows to a stop at a peak altitude. Then returns along the same flight path, at the opposite AOA, gaining speeds as it descends. However, the frisbee does not achieve a curved path similar to a boomerang. See Fig. 4e.

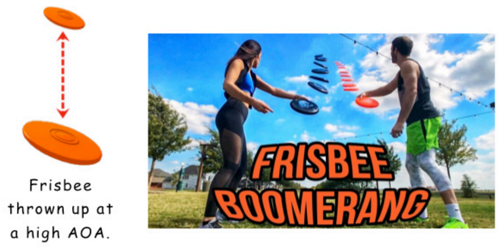


Fig. 4e. Frisbee boomerang trick shot. [45]

A key difference is that the frisbee is designed with a AOA that enables stable, straight forward flight over a long distance. Whereas, a boomerang is designed with a AOA that makes it unstable and unsuitable for such stable, straight, long distance flight.

A few unanswered aspects of frisbee and boomerang flight include:

- It is likely that the frisbees cannot achieve a curved flight path similar to a boomerang because there is no torque of gyroscopic procession?
- Could frisbees achieve a curved flight path similar to a boomerang? For example, by adjusting the pitch and AOA at which it is thrown. This may require a control to ensure that the frisbee has the same AOA as the boomerang.

This analysis and reference to frisbees is significant because it reinforces the assertion that the key part of the boomerang's design that allows it to achieve a curved flight path is the AOA.

V. EXAMPLE CALCULATION

A. *Overview and assumptions.*

The example calculation of the forces exerted by a boomerang below is only an approximation to demonstrate the Newtonian approach described in this paper. A lack of experimental data prevented a calculation from being conducted.

Experimental data and assumptions: See Fig. 5a.

- Standard density of air [1] of 1.2 kg/m^3.
- Boomerang arm length, thickness and diameter (wingspan).
- Boomerang mass.
- Boomerang average AOA (X°).
- Airspeed (m/s).
- Spin speed (m/s)
- The velocity that air is accelerated down (m/s); i.e. 'dv'.

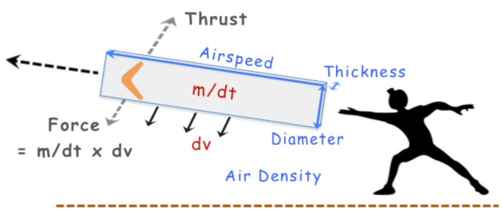


Fig. 5a. Illustration of the key assumptions.

B. *Methodology.*

- First, the volume of air directly flown through is estimated, based on the boomerang's airspeed, thickness, and diameter (wingspan).

Volume of air flown through each second (Volume /dt)
= airspeed * diameter * thickness
= m/s * m * m
= m^3 / s

- Calculation of the mass of air (m/dt) 'flown' through and displaced down each second; using the air density and the volume of air flown through.

Mass/dt = Volume /dt * Air Density
= m^3 /s * 1.2 kg/m^3
= kg/s

- Calculation of the downward force (Force = ma = m/dt * dv); using 'dv'

Force = m/dt * dv
= kg/s * m/s
= Thrust N

- Calculation of the equal and opposite force (thrust), after subtracting the induced drag.

Lift = Thrust * Cos (X°)

A problem is that the boomerang's AOA and orientation is constantly changing over the flight path, making calculations difficult. Nonetheless a computer would be able to do these calculations given accurate assumptions and data.

C. *Summary.*

In summary, the methodology above provides a method to calculate the thrust and lift generated by a boomerang.

The methodology provides a way to prove or refute the Newtonian explanation of how boomerangs fly.

This aspect is new. No other theory of how boomerangs fly provides a method to calculate the forces involved.

This space was intentionally left blank.

VI. Current Theories

A. Prevailing explanations.

There is a lack of academic or scientific research available to explain the physics of how boomerang's fly and the forces acting on boomerangs. Nonetheless, there is some research available.

The prevailing explanations tend to incorrectly focus on the spin and torque as the cause of the boomerang's circular path.

- The Theory of Dynamic Interactions is based the rotational non-inertial dynamics hypothesis, applied to understand both the flight of the boomerang as well as celestial mechanics. [39][40]

  This argument makes absolutely no sense. A comparison of the spin from a boomerang spin to galaxies seems like a stretch.

- The Blade Element Theory was applied to explain a boomerang's flight. [41] This approach uses fluid dynamics, "Unsteady Reynolds-averaged Navier-Stokes solutions provide accurate aerodynamic characteristics of the subject boomerang.

  The high-fidelity aerodynamic model is coupled with the equations of motion to provide accurate six-degree-of-freedom simulations of boomerang flight dynamics. Boomerang orientation during its flight trajectory is described by the classical Euler angles."

Other explanations include applying Bernoulli's principles of fluid dynamics and the pressure differential on the boomerang's arms. [42] But proposed theories tend to exclude any discussion on vortices.

Also contrary to many views, an oncoming wind is not required to throw a boomerang successful, but it helps.

Some explanations speculate that the Magnus effect may play a role in the curved path of a boomerang, similar to how a football can curve in flight when spinning. However, this is unlikely as the boomerang spins along its axis, and not in the direction of travel.

The prevailing explanations tend not include any assessment of the AOA or changes in boomerang speed over the flight path. No do these theories and arguments mention Newtonian mechanics to explain the motion of a boomerang. In addition, no justification is provided for ignoring Newtons Laws of Motion.

B. Gyroscopic forces.

A boomerang, rotor, and propeller are spinning discs, and therefore, act like gyroscopes. This means they have rigidity in space, and precession. Similar to a frisbee, any spin (or rotation around the axis) creates gyroscopic forces that assist the stability of the boomerang in flight, but does not contribute towards lift. See Fig. 6b.

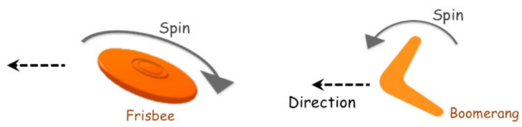


Fig. 6b. Spin on a frisbee and boomerang.

This assertion is demonstrated by the fact that it does not matter which direction the frisbee spins relative to its direction of travel, either clockwise or counter-clockwise. In turn, this means that the gyroscopic effects or gyroscopic progression are not the cause of the boomerang's curved flight path.

A boomerang is always thrown with the same direction of rotation, with the thicker leading edge facing the direction of travel. Therefore, a boomerang cannot be used to demonstrate the assertion that gyroscopic effect do not cause lift.

This assertion is contrary to prevailing view that the boomerang's spin is a key dynamic that affects its curved flight path via gyroscopic effects. There is no evidence that the prevailing view is correct.

C. Torque.

Torque is a force perpendicular to the direction of rotation, along the axis of rotation. Torque is observed in levers and is referred to as moment of force. Torque is defined mathematically as the rate of change of angular momentum of an object. See Fig. 6c.

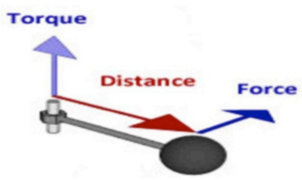


Fig. 6c. Torque.

Torque and angular momentum feature frequently in the prevailing explanations for a boomerang's curved flight path and/or how a boomerang generates lift.

However, a spinning frisbee and propeller exhibit some, but not significant torque, as they are in constant motion and not accelerating. Therefore, it is unlikely that torque applies to boomerangs in flight.

In addition, torque is a relatively weak force. A lot of angular acceleration is required to produce a small amount of torque.

This makes torque even less likely as an explanation for a boomerang's curved path.

D. Other considerations explanations.

Vortices?

Undoubtedly vortices affect a boomerang's flight path and lift. See Appendix II. However, a lack of reliable data makes this impossible to assess and most theories avoid mention of vortices. This paper propose that vortices are only significant to the extend that they affect airflows, and therefore the downward force (Force = m/dt * dv).

Boomerangs and airplane wings

The prevailing explanation of how a boomerang generates lift is based on its airfoil shape. A boomerang is described as generating lift in the same way that an airplane wing or propeller generates lift.

The Newtonian explanation above is consistent with this view that boomerangs, wings and propellers all generate lift in the same way. However, the Newton explain for how a wing generates lift is different to the prevailing view based on fluid mechanics (i.e. Navier-Stokes equations).

Boomerang circular path

The prevailing explanation of a boomerangs circular path is typically based on two factors, which use vectors to describe how lift is generated and how the boomerang spins: [38] See Fig. 6d.

- **The lift force:** The returning trajectory of a boomerang involves the aerodynamic lift of its airfoil shape
- **The spin:** The gyroscopic precession associated with its rapid spin. The precession redirects the airfoil so that it "flies" around the returning path.
- The throw of the boomerang gives it an angular velocity perpendicular to its path as shown. … The spin creates torque, which then causes the circular path.

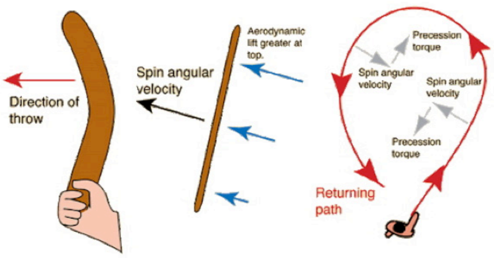


Fig. 6d. Forces acting on a boomerang . [38]

This space was intentionally left blank.

VII. Discussion of Results

It should not be surprising that Newtonian mechanics can explain how a boomerang flies. It would be more surprising to claim that Newtonian mechanics does not explain the motion of a boomerang through the air. Furthermore, it is puzzling that this approach has not been proposed previously.

This is new and original analysis that provides significant new insight into how boomerangs fly, which also helps to resolve the debate regarding the physics of lift.

This explanation differs significantly from the prevailing explanations of lift and the curved path of boomerangs, as provided in physics research journals based on fluid mechanics.

More experimentation needs to be done to confirm the assertions and calculations made by this paper.

VIII. Conclusions

Newtonian mechanics based on the mass-flow rate provides a simple explanation for how boomerangs generate lift and maintain a curved path through the air if thrown correctly. This approach is consistent with what is observed in practice and accepted physics. See Fig. 8a.

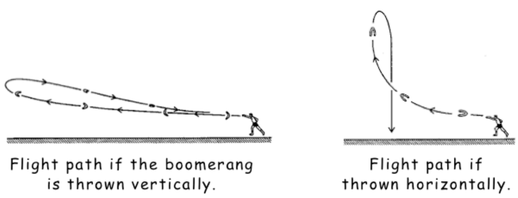


Fig. 8a. Boomerang flight paths
if thrown vertically and horizontally. [42]

IX. Additional information

Author: Mr. Nicholas Landell-Mills, independent researcher.

Corresponding email: nicklandell66@gmail.com

Funding: This paper was self-funded by the author.

Request for financial support: If you found this paper to be useful, entertaining or worthy, then kindly support this independent research with a financial donation to the author via the email address above on PayPal www.PayPal.com. This paper could not have been produced through the established academic and scientific system. Thank you.

Background: The author is British and was born in 1966 in Botswana. He worked in finance for 25 years and held a private pilot's license (PPL) for 20 years. He flew and maintained a small, single-engine, home-built airplane (Europa XS monowheel, G-OSJN).

Academic achievements: The author is a graduate of The University of Edinburgh, Edinburgh, UK. He was awarded a M.A. degree class 2:1 in economics and economic history.

Affiliations: None.

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

Disclaimer: The author confirms and states that all data in the manuscript are authentic, there are no conflicts of interest, and all sources of data used in the paper are acknowledged where possible.

Acknowledgments: None.

ORCID ID: 0000-0003-4814-0443

X. REFERENCES

[1] NASA, Glenn Research Centre. www.grc.nasa.gov

Books:

[2] DF Anderson and S Eberhardt, Understanding Flight (2nd edition); 2010; McGraw-Hill; ISBN: 978-0-07- 162697-2.

[3] "Stick and Rudder" by Wolfgang Langeweische (1944); Ch. 1. (ISBN 978-0-07-036240-6)

Image sources:

[4] Image source: Frisbee Target Trick Shots, Brodie Smith; https://www.youtube.com/watch?v=UbxB6Dvzf18

[5] Images taken from the internet. Unable to identify the source.

Unpublished papers by the author:

[6] N Landell-Mills (2019), Why vertical lift on a wing quadruples if horizontal aircraft velocity doubles; Pre-Print DOI: 10.13140/RG.2.2.20536.70409.

[7] N Landell-Mills (2019), Helicopters achieve buoyancy in a hover; Pre-Print DOI: 10.13140/RG.2.2.27096.55048.

[8] N Landell-Mills (2019), How airplanes generate lift is disputed. Pre-Print DOI: 10.13140/RG.2.2.34380.36487.

[9] N Landell-Mills (2019), Newton explains lift; Buoyancy explains flight. Pre-Print DOI: 10.13140/RG.2.2.16863.82084.

[10] N Landell-Mills (2019), How frisbees fly according to Newtonian physics; Pre-Print DOI: 10.13140/RG.2.2.29948.49281.

[11] N Landell-Mills (2019), The diseconomies of scale in lift generation; Pre-Print DOI: 10.13140/RG.2.2.25191.60327.

[12] N Landell-Mills (2019), How birds fly according to Newtonian physics; Pre-Print DOI: 10.13140/RG.2.2.19558.98885.

[13] N Landell-Mills (2020), How insects fly according to Newtonian physics. Pre-Print DOI: 10.13140/RG.2.2.13994.98247.

[14] Removed.

[15] N Landell-Mills (2020), Animals gliding explained by Newtonian physics; Pre-Print DOI: 10.13140/RG.2.2.27717.60646.

Additional references:

[16] CW McAvoy (2002); Analytical and Experimental Approaches to Airfoil-Aircraft Design Integration; NC State Universities, thesis, Aerospace Engineering, http://www.lib.ncsu.edu/resolver/1840.16/7

[17] K Leoviriyakit and A Jameson, Challenges and Complexity of Aerodynamic Wing Design, Chapter 1, page 2, Dept Aeronautics and Astronautics, Stanford University, International Conference on Complex Systems (ICCS2004), Boston, May 16-21, 2004. See: http://aero-comlab.stanford.edu/publications.html

[18] M Van tooren, J.P.T.J. Berends (2008); Feasilization of a structural wing design problem; DOI: 10.2514/6.2008-2263;

[19] A. Jameson and L. Martinelli (1997); Optimum Aerodynamic Design Using the Navier–Stokes Equations; Theoretical and Computational Fluid Dynamics; (1998) 10: 213–237.

[20] Removed.

[21] W. Thielicke, (2014). The flapping flight of birds: Analysis and application. University of Groningen, Department of Ocean Ecosystems, PhD Thesis.

[22] D.D. Chin, D.Lentink; Flapping wing aerodynamics: from insects to vertebrates; Journal of Experimental Biology 2016 219: 920-932; doi: 10.1242/jeb.042317.

[23] K. Chang (Dec 9, 2003), Staying Aloft; What Does Keep Them Up There? New York Times. See: www.nytimes.com or https://www.nytimes.com/2003/12/09/news/staying-aloft-what-does-keep-them-up-there.html

[24] R Matthews (Jan 1, 2012), The secret to airplane flight. No one really knows. The National newspaper, UAE.

[25] RR Britt (August 28, 2006), How Do Airplanes Fly? in Live Science.: https://www.livescience.com/7109-planes-fly.html

[26] R. Allain, There's No One Way to Explain How Flying Works; Wired Magazine, 22 Feb 2018, Website: https://www.wired.com/story/theres-no-one-way-to-explain-how-flying-works/

[27] E Regis, No One Can Explain Why Planes Stay in the Air. 1 Feb 2020, Scientific American Magazine. https://www.scientificamerican.com/article/no-one-can-explain-why-planes-stay-in-the-air/

[28] J Hoffren (2012), Quest for an Improved Explanation of Lift, AIAA Journal, Helsinki University of Technology, https://doi.org/10.2514/6.2001-872

[29] NF Smith (1972); Bernoulli and Newton in Fluid Mechanics, the Physics Teacher Journal, (AAPT), volume 10; Published online in 2006 at: https://doi.org/10.1119/1.2352317 .

[30] SP Sane, The aerodynamics of insect flight; Journal of Experimental Biology 2003 206: 4191-4208; doi: 10.1242/jeb.00663.

[31] Source: jetphotos.net

[32] Source: rt.com

[33] Image of Davis Wing licensed from Critical Past; www.criticalpast.com .

[34] Images of wing in a wind tunnel licensed from Critical Past; www.criticalpast.com .

[35] Source: youtube: Phoenix FD 3.0 - Wind Tunnel; Nov 2016; https://youtu.be/IOLaoHbuVGY

[36] Klaus Weltner; A comparison of explanations of aerodynamical lifting force; January 1987; American Journal of Physics 55(1):50-54; DOI: 10.1119/1.14960.

[37] Wooden boomerangs. www.woodenboomerangs.com

[38] R Nave, Hyper-physics website http://hyperphysics.phy-astr.gsu.edu/hbase/brng.html

[39] Barceló, G. (2015) Theory of Dynamic Interactions: The Flight of the Boomerang II. June 2014; Journal of Applied Mathematics and Physics, 3, http://dx.doi.org/10.4236/jamp.2015.35067

[40] Barceló, G. (2015) Theory of Dynamic Interactions: The Flight of the Boomerang II. Journal of Applied Mathematics and Physics, 3, 545-555. http://dx.doi.org/10.4236/jamp.2015.35067.

[41] J. Vassberg; Boomerang Flight Dynamics; June 2012; DOI: 10.2514/6.2012-2650; Conference: 30th AIAA Applied Aerodynamics Conference.

[42] Y Nishiyama, Why do boomerangs come back?; International Journal of Pure and Applied Mathematics; Volume 78 No. 3 2012, 335-347, ISSN: 1311-8080 (printed version); http://www.ijpam.eu

[43] J.R. Usherwood, J.A. Cheney, J. Song, S.P. Windsor, J.P. J. Stevenson, U. Dierksheide, A. Nila, R.J. Bomphrey, High aerodynamic lift from the tail reduces drag in gliding raptors; Journal of Experimental Biology 2020 223: jeb214809 doi: 10.1242/jeb.214809; Published 10 February 2020.

[44] Images taken from a Nature Video from youtube, 10 Oct 2020. https://www.youtube.com/watch?v=2sh8_3-R90I

[45] How to throw a frisbee boomerang ; Brodie & Kelsey; Oct 19, 2017; YouTube channel: Darkhorse and The Dancer with Brodie & Kelsey; https://youtu.be/XRZTL1GZnUU

[46] Boldmethod. www.boldmethod.com .

[47] J. Walker; How to make a boomerang; blog / website: http://makerstutorial.blogspot.com/2008/08/how-to-make-boomerang.html

[48] Y. Nakamura, N. Fukamachi; Visualization of the flow past a frisbee; Fluid Dynamics Research, Volume 7, Issue 1, pp. 31-35 (1991). Jan 1991; DOI: 10.1016/0169-5983(91)90004-3 .

[49] BD. Recktenwald, G. L. Crouse, A. Ahmed; Experimental Investigation of a Circular Planform Joined Wing Concept Aircraft; May 2010; Journal of Aircraft 47(3):887-894 ; DOI: 10.2514/1.46149;

[50] Removed.

APPENDIX I – UNRESOLVED THEORY OF LIFT

A. The theory of lift is unresolved. [8]

The physics of lift is disputed. There is no scientific experiment on a real aircraft in realistic conditions that proves any theory or equation for lift to be true.

Fig. I-a. Unknown.

Experts still cannot agree whether aircraft generate lift by being pulled upwards according to fluid mechanics, or pushed upwards according to Newtonian mechanics; nor exactly what role vortices play. This is surprising given airplanes have been flying for over a hundred years.

Academics, engineers, aircraft manufacturers, pilots, aviation authorities, and other pundits (e.g. NASA) promote over twelve diverse theories of lift. New theories are occasionally proposed.

Worse, there is no accepted universal theory of how lift is generated that applies to all objects that fly. Airplanes, helicopters, birds and insects each have their own unique explanations. Different theories are used to explain lift in different insects. This aspect is highly inconsistent.

B. Media and academic commentary.

The media occasionally comment on the ongoing debate about the mysterious, unproven and unknown causes of lift:

- "Staying Aloft; What Does Keep Them Up There?" in New York Times, 2003. [23]
- "How Do Airplanes Fly?" in Live Science, 2006. [25]
- "The secret to airplane flight. No one really knows." in the National Newspaper, 2012. [24]
- "There's No One Way to Explain How Flying Works," in Wired Magazine, 2018. [26]
- "No One Can Explain Why Planes Stay in the Air." in the Scientific American magazine, 2020. [27]

Academic journals occasionally address this issue as well:

- "Quest for an Improved Explanation of Lift," in the AIAA journal, 2012. [28];
- "….to date, flapping flight is not fully understood." [21]
- "….there are still myriad open questions about how animals fly with flapping wings," [22]

C. Academics, engineers, pilots, pundits, …..

Various groups promote at least twelve radically different theories of flight, which include:

- **Academics and engineers** prefer complex models based on **fluid mechanics** (e.g. Bernoulli, Navier-Stokes, Euler, ….). They frequently confuse mathematical proof, wind tunnel experiments or computer simulations (e.g. CFD) for scientific evidence.
- **Aircraft manufacturers and designers** (e.g. **Burt** Rutand) design wings by **intuition, trial and error,** rather than by any particular theory or equation for lift. [16][17][18][19]

  Similarly, micro unmanned vehicles (drones) are simply built to **mimic bird and insect flight**, without the designers fully understanding the physics involved.
- **Pilots** prefer **Newtonian based theories of lift.** Simply put, wings push air downwards and the reactive equal and opposite force pushes the airplane upwards. Momentum is transferred from the airplane to the air.
- **NASA** sits on the fence in this debate, and supports both explanations of lift. "So **both Bernoulli and Newton are correct**." [1] NASA fails to state what proportion of lift is explained by Bernoulli and Newton; 50/50? Or 70/30?

  However, both Newtonian and fluid mechanics cannot be true as they provide very different and incompatible explanations of lift. How can NASA not know which theory of flight is correct?
- **Aviation authorities** (e.g. FAA, CAA, EAA; …) recommend that pilots are taught a theory of flight based on the **Venturi effect and Bernoulli's principles** of fluid dynamics. NASA describes this theory to be incorrect' [1] and academics discredited Bernoulli's theorem as an explanation for lift at least as early as 1972. [29]
- **Other groups** promote a mixture of different theories of lift based on vortices, the Magnus effect, the Coanda effect, …..
- Some group advocate that the **pressure differential** on a wing explains lift. However, pressure is a consequence of a force (Pressure = Force/Area), not a cause. Correlation of pressure and lift on a wing does not prove causality.
- **Empirical observation:** The **factors** that affect lift in practice have been observed and measured; as summarized by the standard equation for lift: [1]

$$\text{Lift} = 0.5\,(\text{Aircraft Velocity}^2 * \text{Air Density} * \text{Wing Area} * \text{Lift Coefficient})$$

However, this equation only describes the factors that affect lift; it does not explain why these factors affect lift.

In particular, fluid mechanics fails to explain the physics of the standard equation for lift, but Newtonian mechanics can. For example, only Newtonian mechanics can explain why lift quadruples if aircraft velocity doubles.

Appendix II – Airflow Analysis

A. Two absolute airflows.

Airplane wings (boomerang arms) with a positive AOA have two separate absolute airflows involved in the generation of lift. See Fig. II-a-i and II-a-ii.

1) The underside of the wing pushes air down.

2) The topside of the wing pulls air down.

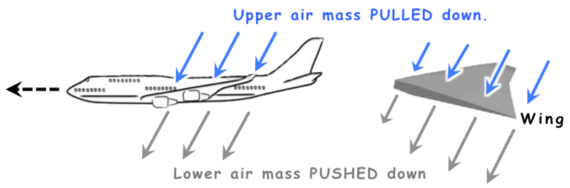


Fig. II-a-i. Two airflows on a wing.

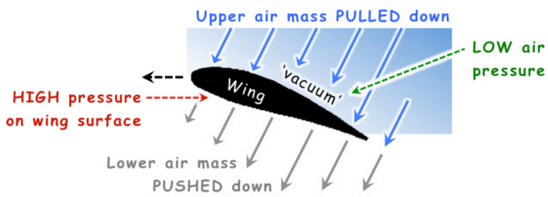


Fig. II-a-ii. 2D diagram of wing airflows.

Some considerations:

- The faster the wing flies, then:
  - The greater the force applied by the underside of the wing to accelerate the lower airflow downward to a higher velocity (dv).
  - The stronger the vacuum or low air pressure on top of the wing that is created, and the faster the upper mass is pulled down (dv).
- The upper and lower airflows can have different velocities (dv) as they have different causal forces. Nonetheless, their velocities are likely to be similar. Therefore, the two airflows create similar low internal air pressures, due to their increased velocity.
- The low-pressure created on top of the wing and the high-pressure created below the wing, are a consequence of the airflows and resultant forces. i.e. The pressure patterns observed are not a direct cause of lift.
- This explanation is somewhat different to the standard or prevailing description of wing airflows. Typically the lower airflow is described as 'high pressure', which is inaccurate and misleading.

  It is more accurate to say that the underside of the wing experiences high pressure, and the lower airflow experiences low internal air pressure.

The two wing airflows are described:

3) **The underside of a wing** physically pushes the air flown through below it downwards and slightly forwards. This creates high pressure on the underside surface of the wing, based on the standard equation for pressure (Pressure = Force /Area [1]). See Fig. II-a-iii.

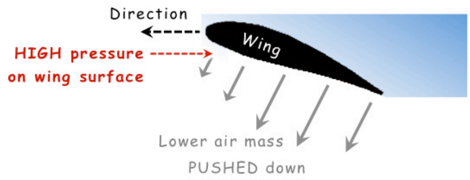


Fig. II-a-iii. Underside of the wing pushes air down

4) **On the topside of the wing** a zone of low air pressure arises, due to the forward movement of the wing creating a relative vacuum (void) behind it. See Fig. II-a-iv.

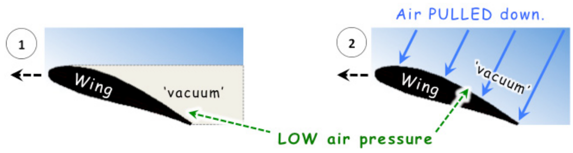


Fig. II-a-iv. Vacuum behind the topside of the wing.

The atmosphere above the wing pushes the upper air mass downwards towards the top of the wing, helped by gravity. Also, the low air pressure pulls the air above the wing downwards. After the wing has passed, the upper air mass continues to descend.

In addition:

- Any curvature on the topside of the wing can enhance downward airflows of the air above the wing due to the Coanda effect, as explained below.
- The air above the wing pulled downwards reaches the trailing edge on the wing, to avoid triggering a stall.
- The low air pressure on top of the wing is typically described as being greatest towards the leading edge.
- The theoretical path of an air molecule starting above the wing and travelling downward, as the wing passes through the air, is illustrated in Fig. II-a-v.

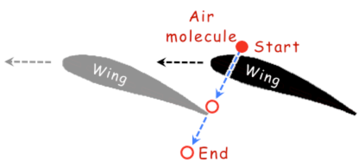


Fig. II-a-v. Theoretical path of an air molecule starting above the wing.

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 re-directed by the curved side of a spoon demonstrating the Coanda effect, as illustrated in Fig. II-b-i.

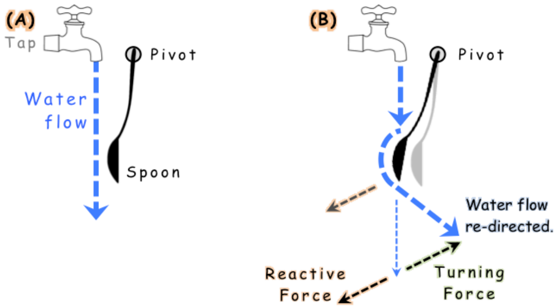


Fig. II-b-i. Coanda effect – Spoon experiment.

According to Newtonian mechanics, the water flow passively re-directed by a spoon due to the Coanda effect creates a small turning force due to the change in momentum of the water flow. The reactive equal and opposite force pushes the spoon diagonally to the left sideways and downward. However the spoon pivots to the left as far as the reactive force allows.

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. II-b-ii.

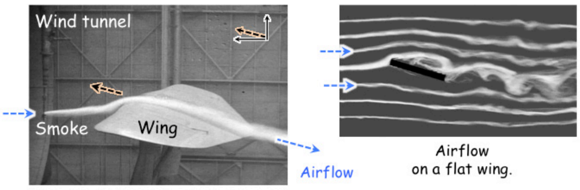


Fig. II-b-ii. Airflow on curved and flat wings. [33][35]

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). See Fig. II-b-iii.

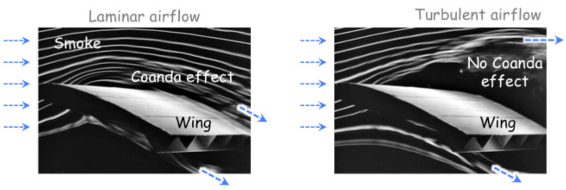


Fig. II-b-iii. Smooth vs. turbulent airflows on a wing. [34]

The flat undersides of wings are typically designed to push air down without inducing any Coanda effect.

C. *Airflow diagrams.*

The wing airflow diagrams used by fluid mechanics shows the air moving relative to a stationary wing, similar to what is seen in wind tunnel experiments. See Fig. II-c-i.

On the other hand, this paper focuses on absolute airflows created by an airplane wing (or frisbee disc) according to Newtonian mechanics. Diagrams show a wing displacing static air downwards and slightly forwards, which circulates the air behind the airplane. See Fig. II-c-i.

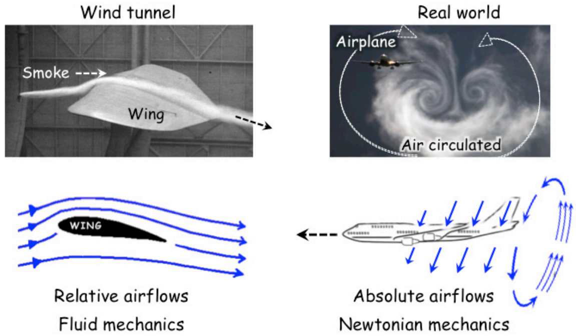


Fig. II-c-i. Relative and absolute wing airflow diagrams.

Both diagrams are correct, as they show the same airflow but in different ways. This paper argues that relative wing airflows are useful for analyzing aerodynamics, whereas absolute airflows are useful for analyzing the lift force generated.

Airflow patterns observed in practice.

The absolute airflows that arise in practice, can be observed by commercial airliners flying through clouds. See Fig. II-c-ii.

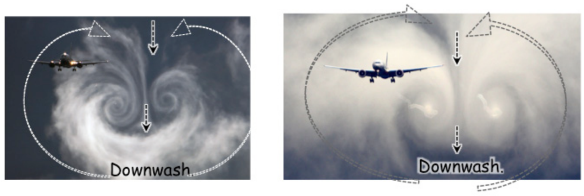


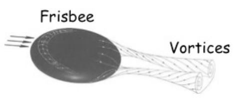
Fig. II-c-ii. Evidence of airplanes circulating the air. [31][32]

Fig. II-c-iii. Raptors flying through soap bubbles. [43][44]

Similar to airplanes, frisbees generate two counter-rotating masses of air, centered on two wingtip vortices, either side of the frisbee.

D. Vortices.

Vortices are regularly observed in relation to wing movements and lift generation, including frisbees. This is especially at extreme wing AOA and particularly in insects and birds. Exactly how vortices create lift is rarely clarified in any research. There is no definitive experiment that proves vortices cause lift, nor any accepted equation that describes the relationship accurately. See Fig. II-d-i.



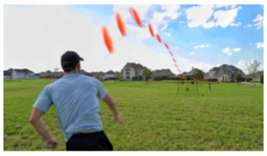


Fig. II-d-i. Vortices arise on a frisbee, and frisbee trick shot. [4]

But correlation is not causation. It is wrong to assume that vortices cause lift because they are observed to occur during lift. Vortices may be a consequence not a cause of lift.

This paper does not consider vortices to be a primary cause for lift and does not analyse them in detail. Vortices can augment or detract from lift depending on the circumstances. For example, vortices and other factors like the Magnus effect can help explain many 'trick' frisbee throws.

Leading edge vortices (LEVS).

Insects and delta wing jets are thought to use LEV to allow for flight at unusually high angles of attack. LEVs appear to permit wings to avoid a stall at a high AOA. See Fig. II-d-ii.

Fig. II-d-ii. LEVs on delta wing airplanes.

According to Newtonian mechanics, vortices enhance or detract from lift depending on the circumstances and how they impact 'm/dt' and 'dv' of the downwash, and therefore lift (Lift = m/dt * dv). For example, LEVs on a bee's wing can increase the 'm/dt' and 'dv' of the downwash, and therefore, the lift generated. See Fig. II-d-iii.

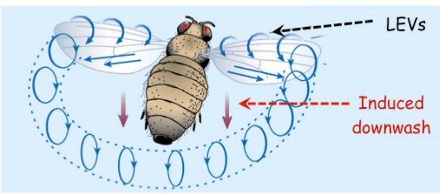


Fig. II-d-iii. Leading edge vortices on a bee's wings. [30]

This space was intentionally left blank.

APPENDIX III – HOW FRISBEES FLY

*A. Lift = m/dt * dv. [10]*

Where:
- m = Mass of air flown through and pushed down.
- m/dt = 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 down.
- a = dv/dt = Acceleration.
- Momentum = mv [1]

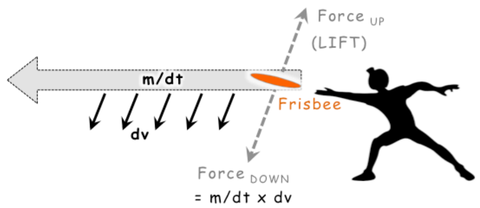


Fig. III-a-i. Newtonian forces acting on a frisbee. 1

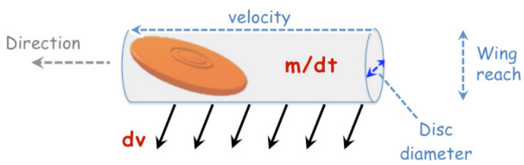


Fig. III-a-ii. Newtonian forces acting on a frisbee. 2

Simply put, the frisbee pushes air down as it flies forwards, causing the frisbee to be pushed up. According to Newtonian mechanics based on the mass flow rate, for a frisbee in stable flight through static air, which has a positive angle of attack (AOA). The frisbee flies through a mass of air each second (m/dt), which it accelerates to a velocity (dv) downwards. This action crates a downward force: See Fig. III-a-i and III-a-ii.

$$\text{Force}_{\text{DOWN}} = \text{ma} = \text{m/dt} * \text{dv} \qquad (1)$$

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:

$$\text{Force}_{\text{DOWN}} = \text{Force}_{\text{UP}} \text{ (Lift)} \qquad (2)$$

Lift is the vertical component of the upward force. If induced drag is negligible, then lift equals the upward force:

$$\mathit{Force}_{UP} = \mathit{Lift} \qquad (3)$$

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

$$\mathit{Force}_{DOWN} = \mathit{Force}_{UP} = \mathit{Lift} = m/dt * dv \qquad (4)$$

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

$$\text{Units:} \quad N = kg/s * m/s$$

In these equations above the increased velocity of the air is expressed as ‘dv’, and not as acceleration (‘dv/dt’), because this action is not time dependent. It is due to a one-off force (impulse) from the frisbee. In contrast, the mass of air flown through by the frisbee is time dependent, and therefore, is expressed as the mass flow rate (m/dt).

In terms of airflows, the underside of the frisbee pushes the air down. Whereas a vacuum of low air pressure on the topside of the frisbee pulls air down, helped by the Coanda effect.

Evidence of downwash behind a frisbee is provided by wind tunnel experiments. [48] See Fig. III-a-iv.

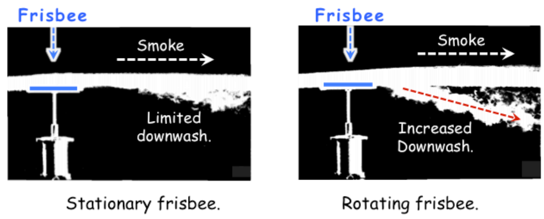


Fig. III-a-iv. Downwash from a rotating frisbee. [48]

B. Spin on a frisbee

The spin on a frisbee enhances the stability of flight due to its gyroscopic effects. In turn, stability of flight allows the frisbee to generate lift effectively by maintaining laminar (non-turbulent) airflows as much as possible. The frisbee’s spin itself does not directly enhance vertical lift. [49] This is demonstrated by the fact that it does not matter which direction the frisbee is spun, either clockwise or counter-clockwise. See Fig. III-b.

Fig. III-b. Spin on a frisbee.

C. The Coanda effect on frisbees

Frisbees’ curved top-side provides minimal turbulence and maximizes the Coanda effect and therefore the amount of air displaced down. The Coanda effect is extremely significant to the lift generated by a frisbee. The Coanda effect is illustrated using relative airflows, where the frisbee is shown as static and the airflows are shown as moving. See Fig. III-c

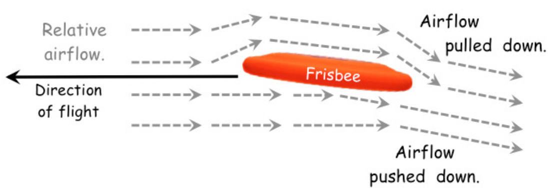


Fig. III-c. Relative airflows showing the Coanda effect.

Appendix IV – Propellers and Adverse Yaw

A. Boomerang vs. propeller forces.

If a boomerang was spun in a static position, then it should generate forces similar to a propeller on a stationary airplane. Any differences in the forces created by a static boomerang and propeller can be explained by differences in their shape and design. For example, blade thickness, AOA, blade length, … See Fig. IV-a.

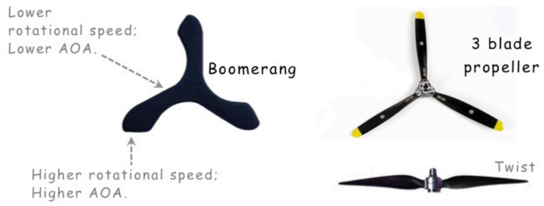


Fig. IV-a. Boomerang and propeller compared.

A key difference is that propellers have a twist along their wingspan. The pitch alters from the tip to the hub, to ensure a constant AOA to the direction of travel (or relative wind).

In contrast, boomerangs typically have no twist. This means that the tips of the boomerang, which are spinning at high speed, have a higher AOA as compared to the center of the boomerang, which are spinning at a low speed.

Also, propellers tend to be deeper (higher chord) close to the hub, as compared to the propeller tip, which is similar to boomerangs.

Therefore, the Boomerang's lack of twist, as compared to a propeller, produces an uneven AOA across the length (diameter) of the boomerang. In turn, this could help account for the boomerang's curved flight path.

This space was intentionally left blank.

B. P-Factor and propellers. [9]

Asymmetric propeller loading, or a 'P-Factor', which causes an airplane to yaw to the left on take-off, is consistent with the forces acting on a boomerang.

An example of asymmetric propeller loading is a single engine airplane such as a Cessna 172 on take-off (nose-up configuration), at a high power and high AOA, can experience yaw to the left. The standard explanation is that the left yaw arises under these circumstances because:

- The downward propeller blade (on the right side of the cockpit) experiences a higher AOA; while the upward propeller blade (on the left side of the cockpit) experiences a lower AOA.

  In turn, the change in propeller AOA arises because there is an increased load on the downward moving propeller; and correspondingly, a decreased load on the upward moving propeller.
- This causes the downward propeller to generate greater thrust, and the upward propeller to produce less thrust.
- The combined shift in propeller thrust induces a yaw to the left in the airplane. See Fig. IV-b-i and IV-b-ii.

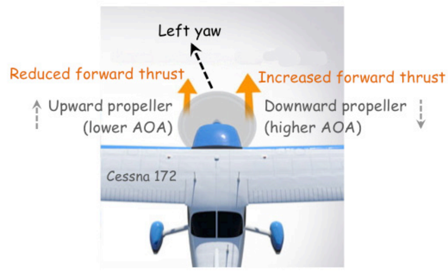


Fig. IV-b-i. P-Factor and left yaw – top view. [46]

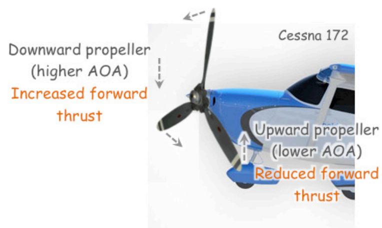


Fig. IV-b-ii. P-Factor and left yaw – side view. [46]

However, if the propeller AOA changes, then it is the direction that the thrust changes on both sides of the propeller (towards the left), not the quantity of thrust. See Fig. IV-b-iii.

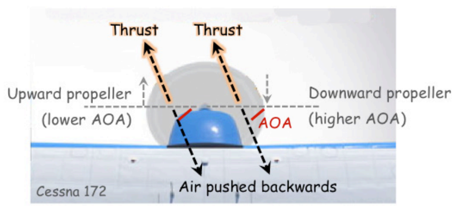


Fig. IV-b-iii. P-Factor and left yaw. [46]

C. Adverse yaw on airplanes. [9]

Adverse yaw

An adverse yaw arises in a stable bank, at constant altitude and airspeed. Banking also causes the airplane's nose to rise upward, and the wings pivot around the airplane's center of gravity.

In the example below, the raised right wing pivot backwards and the lowered left wing pivots forwards. The adverse yaw creates an unsymmetrical bank and is aerodynamically undesirable; as the airplane rotates (or pivots) around its center of gravity. See Fig. IV-c-i.

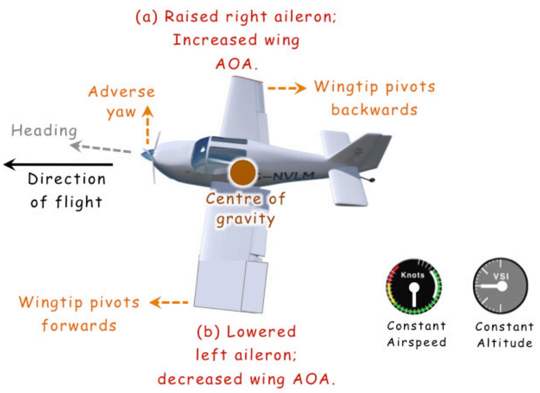


Fig. IV-c-i. Adverse yaw in a bank.

Adverse yaw in a bank is negative for the aerodynamics of the airplane and the airplane is considered to be in an unbalance turn. It can be corrected by applying the opposite rudder, to push the nose to the airplane down. towards the direction of flight.

Adverse yaw explained

Adverse yaw is explained by the opposite forces acting on the two wingtips: See Fig. IV-c-ii.

- At the wingtip in this example: the right aileron (a) is lowered and extends below the profile of the wing, which increases the wing AOA.

  This action pushes more air flown through by the wings downwards (higher m/dt) at a less steep (flatter) angle to the vertical direction, as compared to the rest of the wing.

  The net effect is to:

  - Increase lift generated at the right wingtip, pulling it upwards.
  - Increase the induced drag at the right wingtip, as the lift is generated at a more oblique angle. In turn, this change causes the wingtip to be pulled backwards. Consequently, the airplane pivots or rotates clockwise around its center of gravity, creating adverse yaw.

- The reverse process occurs on the left wingtip: The other (left) aileron (b) extends above the profile of the wing.

  This action pushes more air flown through by the wings upwards (higher m/dt) at a steeper angle to the vertical direction, as compared to the rest of the wing.

  The net effect is to:

  - Generate negative lift at the left wingtip, pulling it downwards.
  - Create forward induced drag at the left wingtip, causing the left wingtip to be pulled forwards. Consequently, the airplane pivots or rotates clockwise around its center of gravity, creating adverse yaw.

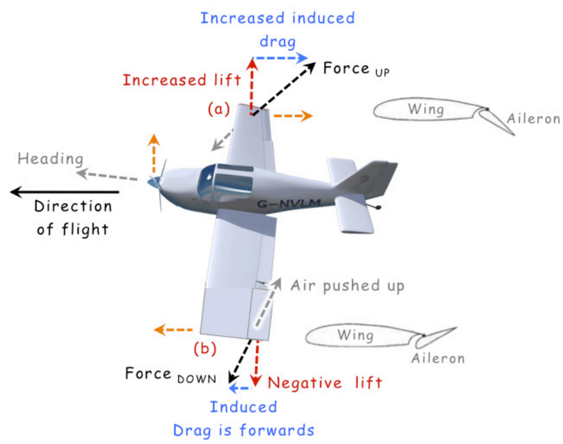


Fig. IV-c-ii. Forces acting on an airplane in a bank.

The 2D list distribution pattern across the wing at the start of a bank is shown in Fig. IV-c-iii.

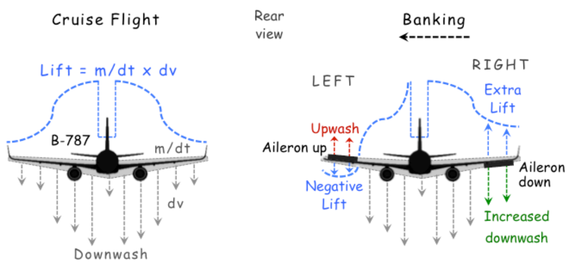


Fig. IV-c-iii. 2D lift distribution at the start of a bank.

The additional forces created at the wingtips by the ailerons in a bank can be calculated using Newtonian mechanics based on the mass flow rate: Lift = m/dt * dv. The additional lift (or negative lift) created is the additional 'm/t' and 'dv' created by the ailerons.

In other words, an adverse yaw arises due to the ailerons altering the 'dv' at the wingtips. This action changes the lift (Lift = m/dt * dv) and induced drag distribution across the wing, to cause the airplane to pivot the nose up in a bank. See Fig. IV-c-iv.

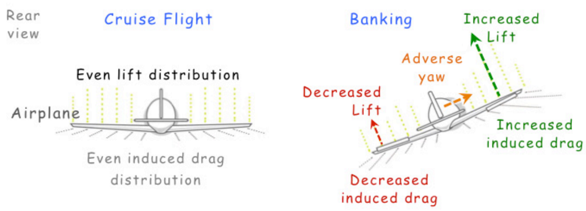


Fig. IV-c-iv. Lift and induced drag distribution across a wing of an airplane in stable cruise flight.