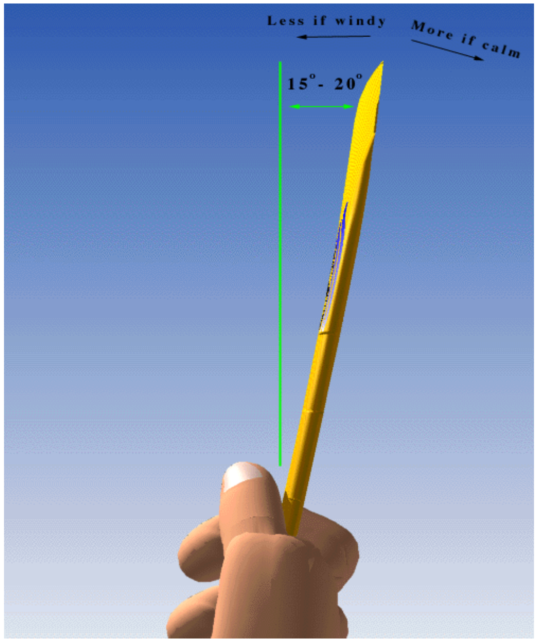
NES

Monday February 2009

Will my boomerang come back?



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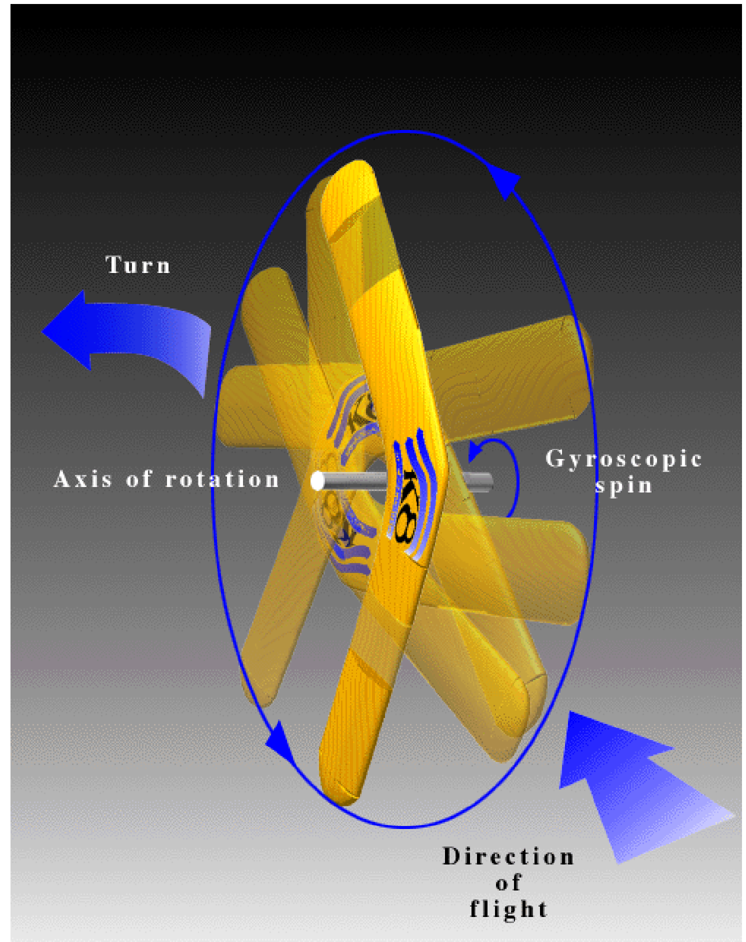
What is a boomerang?

- A boomerang is a multi-winged rotating flying object.
- Its interesting flight path is a consequence of the asymmetrical arrangement of its wings.
- A boomerang differs from a helicopter because it has no 'on board' source of propulsion.
- Its motion is derived entirely from its initial launch impetus.
- How does it do what it does; that is the question?



Structure of my talk

- I will start with a short history of what we know about real world rotating flying devices.
- We will then look at what basic physics has to say about these devices.
- To understand lift, and hence the concept of an aeroplane, we will have to look at the interaction between fluids and solid objects.
- An important aspect needed in understanding our boomerang's flight is gyroscopic stability. We will briefly look at this by observing the motion of a gyroscope.
- Finally we will look at a range of impulse launched rotating flying objects.

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Short history of flying rotating objects – in particular boomerangs

- Boomerangs have a long history
  - Amongst the earliest evidence is the find in Poland of ivory ‘killing sticks’ (20,000 years old!). These appear to have been made from walrus tusks.
  - There is evidence that boomerang like objects existed in the Middle East about 5000 years ago (Pharaonic burials including that of Tutankhamun).
  - Evidence also exists in India and in USA (Hopi) in temple sculptures and rock paintings.

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Short History

- Australian rock paintings hint that there is also a long history there; perhaps many 1000s of years. Oral tradition going back many generations, amongst many of the aboriginal families, keeps alive the craft skills for boomerang manufacture.

- Other than the Greek discus, rotating discs have a much more recent history largely due to the technological difficulties of producing perfect (or nearly perfect) discs. A possible exception is the chakram, a 400yr old Sikh weapon.

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What Physics do we need to know about to understand the behaviour of these devices?

- Newton's Laws of motion for rigid bodies
  - Linear
  - Angular
- Conservation Laws
  - Matter
  - Momentum
  - Energy
- Fluids
  - Ideal fluids
  - Real gases

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Objects in flowing fluids

- In the case of a boomerang, we need to understand how solid rotating/moving objects interact with a fluid – in its simplest form a solid surface with a flowing gas.

- In general, the fluid is highly compressible (i.e. the gaseous mixture - air) and is viscid.

- We will see that because of the interaction the fluid flowing past a fixed object (or, indeed, a moving object in a stationary fluid) can produce local fluid rotation i.e. vortices.

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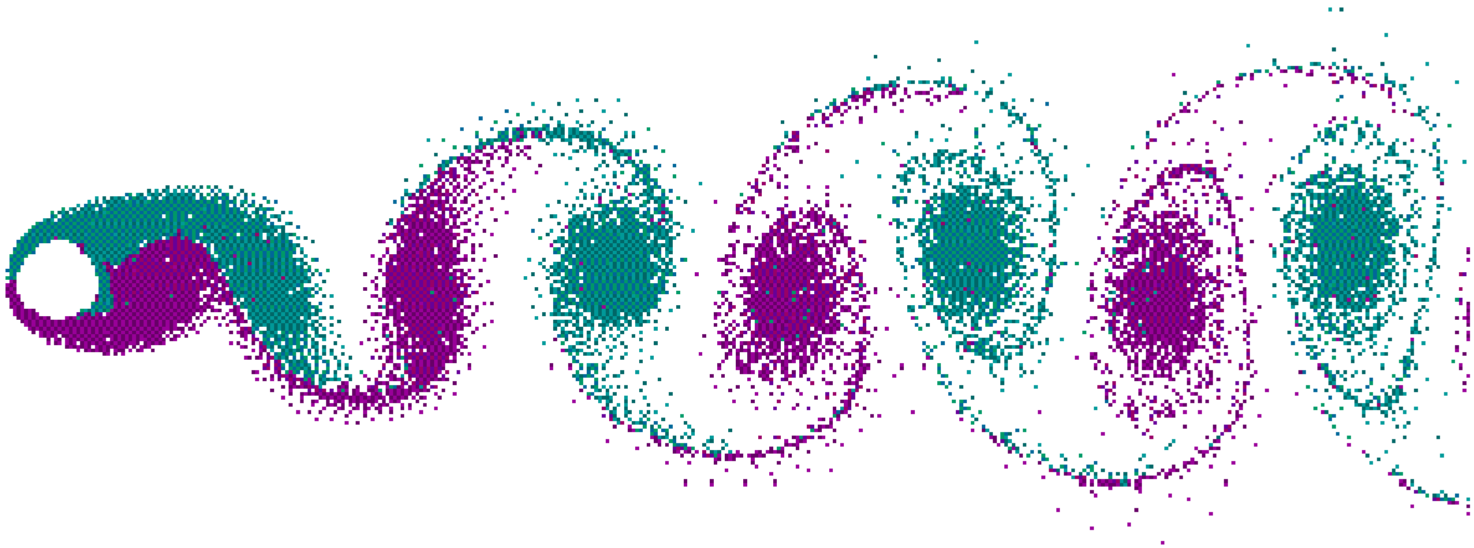
Fixed spherical object in a flowing fluid



Another classic example is the tip vortex shed from an airplane wing

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Another example – note the scale

How do our devices fly?

- All earth bound flying devices are subject to the over-riding gravitational field i.e. if there is no counterbalancing force all objects move towards the centre of the earth.
- We also know that when a body is projected in this field it follows a parabolic path if air resistance is neglected. In general, if resistance is included, the body returns to the earth's surface quicker than this ideal case with a shorter range.
- However it has been found that for certain shaped objects this range can be extended greatly; indeed, in the case of an aeroplane indefinitely provided energy can be supplied indefinitely. In this case the object is said to 'fly'.
- How can this be?

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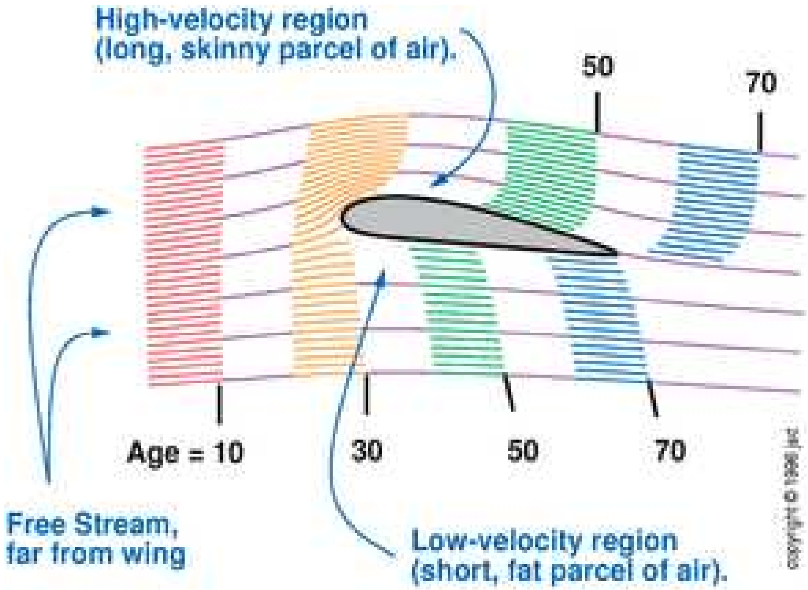
Wings and lift

- Before considering rotating objects, let us look at the apparently simpler problem of fixed wing flight.

- Consider the simplest possible wing – assumed infinite in length and aligned perpendicular to line of motion.

  Note: This overcomes possible problems associated with wing tip vortices

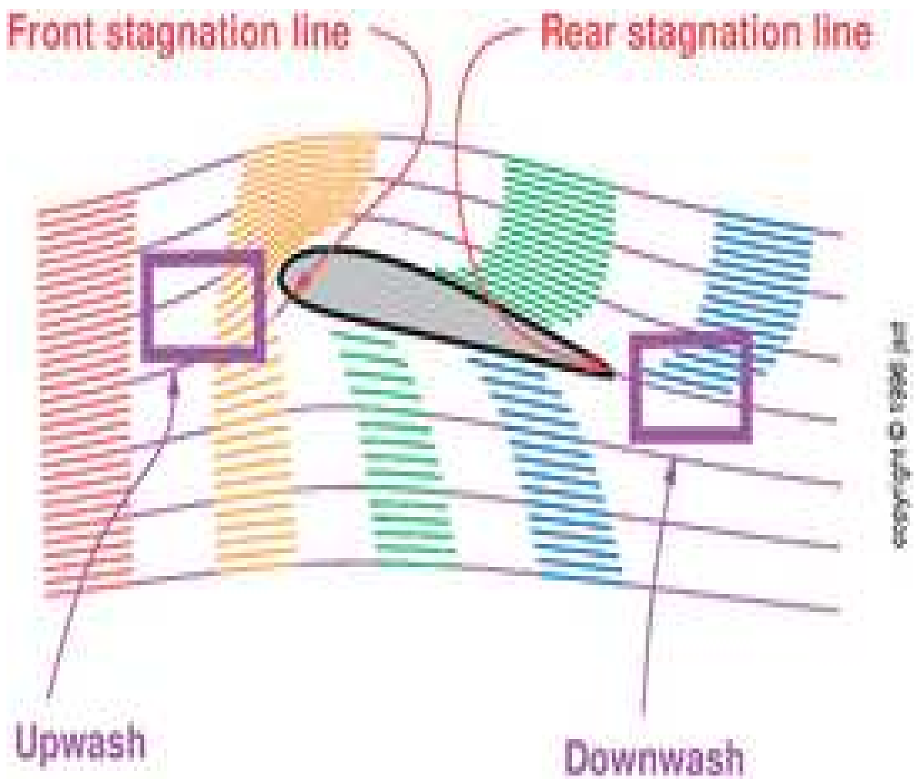


Wings and lift

- If this simple model is looked at in more detail two effects need to be accounted for i.e. ‘up wash’ and ‘downwash’.

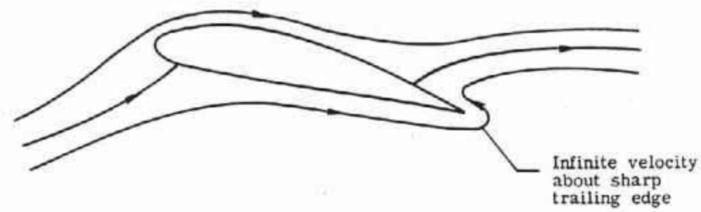
- At low angle of attack, i.e. major axis of wing almost lying along the direction of the relative flow, downwash momentum exceeds the up wash momentum provided that the wing is more curved on top than on the bottom.

- The net effect is that, by Newton’s third law, the wing section experiences an upward force i.e. lift.

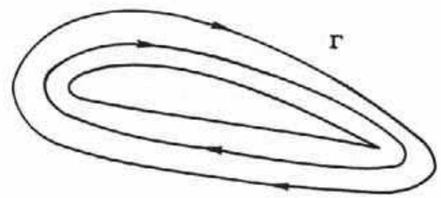


Wings and lift

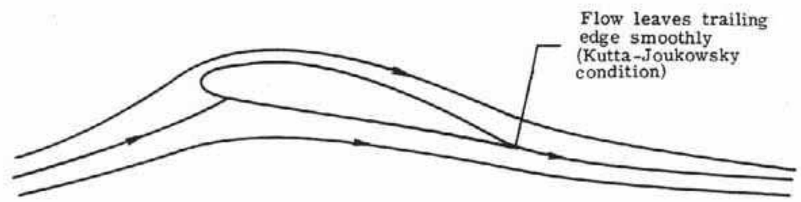
- The motion of a wing can crudely be thought of as circulation around the wing superimposed on top of flow.
- An important point to note is that at the trailing edge there would be an infinite velocity gradient if nature didn't 'smooth' it out in some way.
- Another consequence of circulation is that to conserve angular momentum in the fluid as a whole, there must be a vortex downstream of the wing with exactly the opposite angular momentum to that associated with the circulation around the wing.



(a) Flow with no circulation.



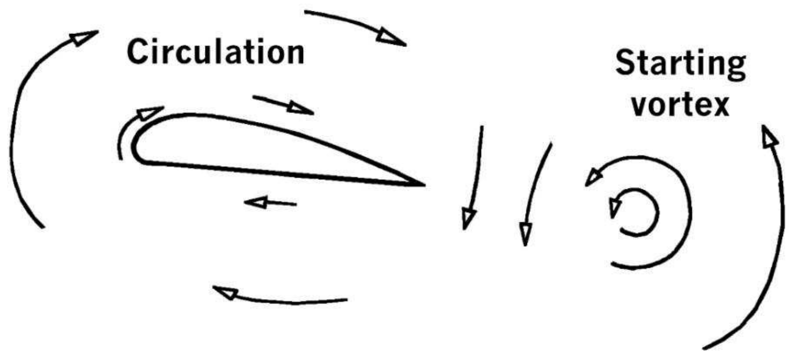
(b) Circulatory flow only.



(c) Flow with circulation.

Wings and lift

- This vortex must always be maintained whilst circulation around the wing continues.
- Because of viscous drag, energy must be continually being lost in this vortex.

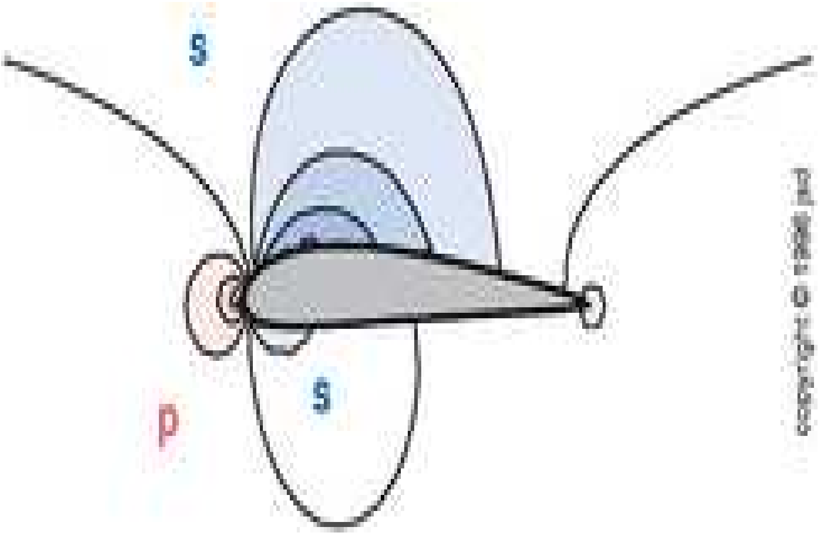


Wings and lift

- If a detailed calculation is performed on the wing assuming streamlined flow then the plot shows that the pressure is lowest where the streamlines have their highest positive curvature.

- Using these pressure calculations, the overall lift for a unit length of the effective infinite wing can be determined as a function of the angle of attack. This determines the so called lift coefficient, C_L.

- It is also possible to determine the drag associated with this wing section. This determines the drag coefficient C_D.



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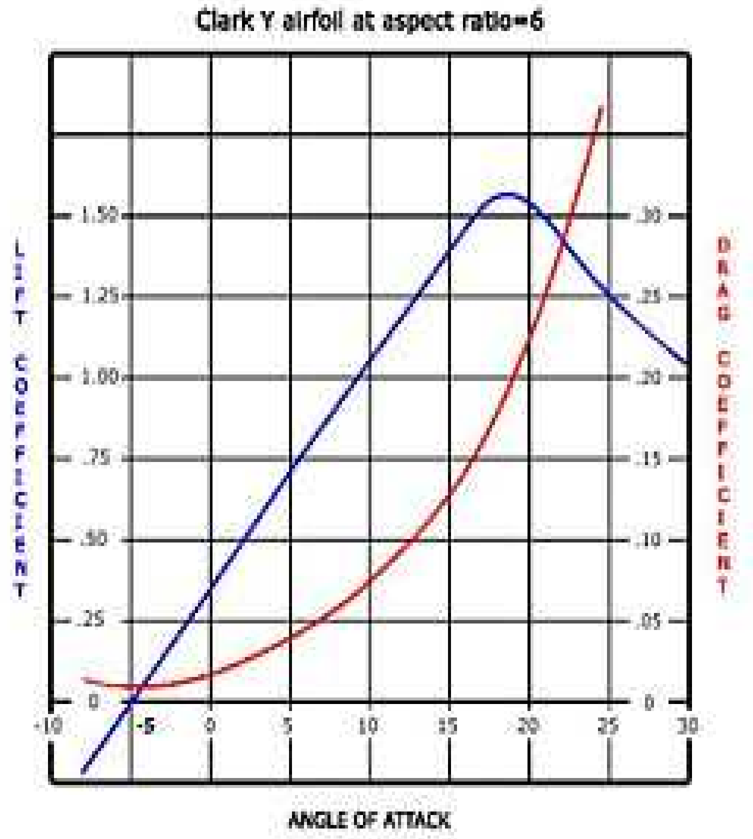
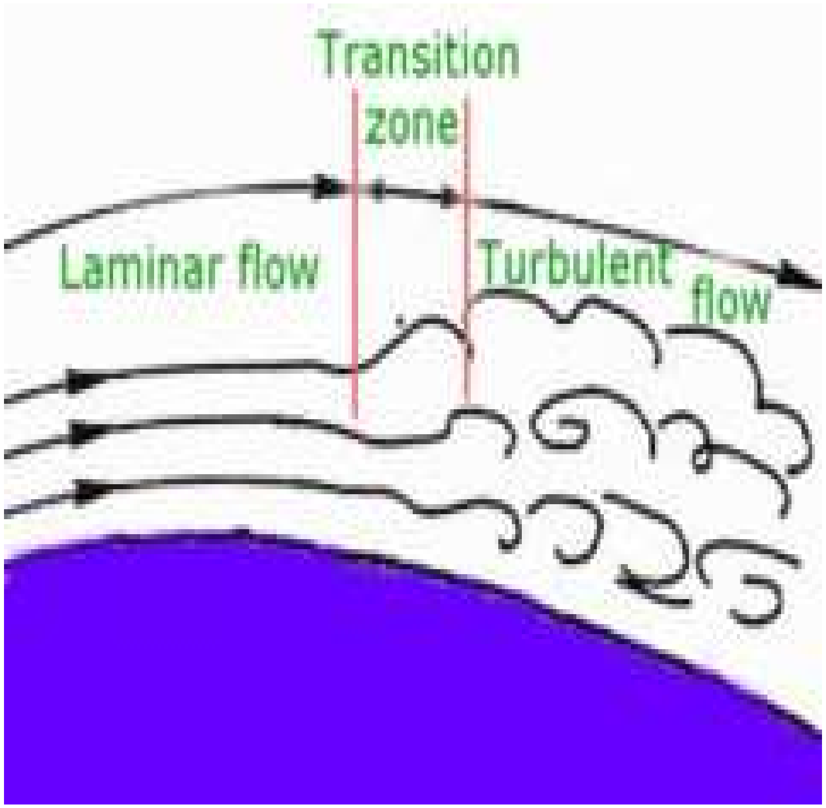
Lift and drag

- At low angles of attack this theory corresponds to empirical observations.
- However at 20 degrees or so the lift suddenly appears to drop whilst drag continues to rise.
- This is the so called ‘stall’ condition.
- Clearly to be avoided.



Problems with the simple lift ideas

- The major problem is that the real effect of viscous drag has been ignored. Close to the wing surface there is high velocity shear.
- Because of the viscous drag this produces local rotation i.e. small scale vortices The vortices themselves interact and cause local heating
- Initially at the leading edge these vortices behave as if they are confined to a thin layer close to the wing – the so called boundary layer
- Unfortunately as the fluid passes along the wing surface the layer contains sufficient energy to expand rapidly in thickness.
- The net effect of this is to reduce the effective lift area and increase the drag



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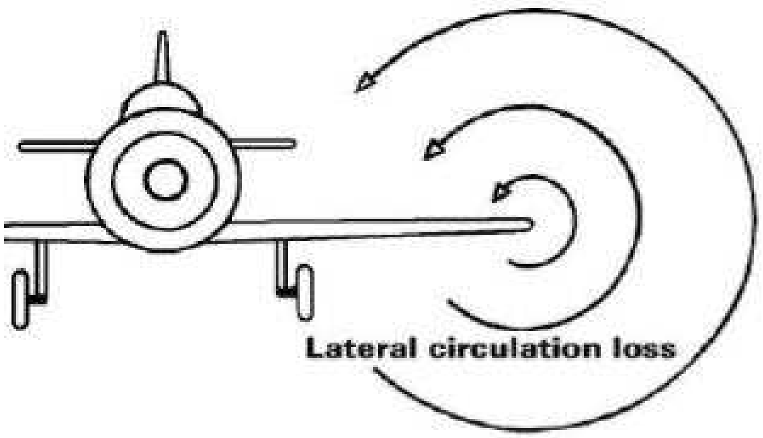
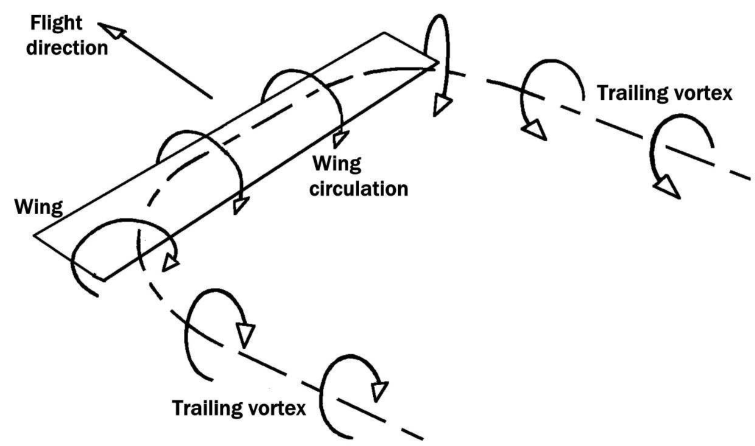
Problems with the simple lift ideas

- To try to equalise the pressure difference between lower and upper wing surfaces, finite wings lead to circulation around the wing tips. This flow tends to reduce the pressure difference and thus reduce lift.



- Consequences are that lift is reduced and the drag increased compared to the ideal wing cross-section



- This extra set of vortices is a major contributor to the overall drag of a given wing.

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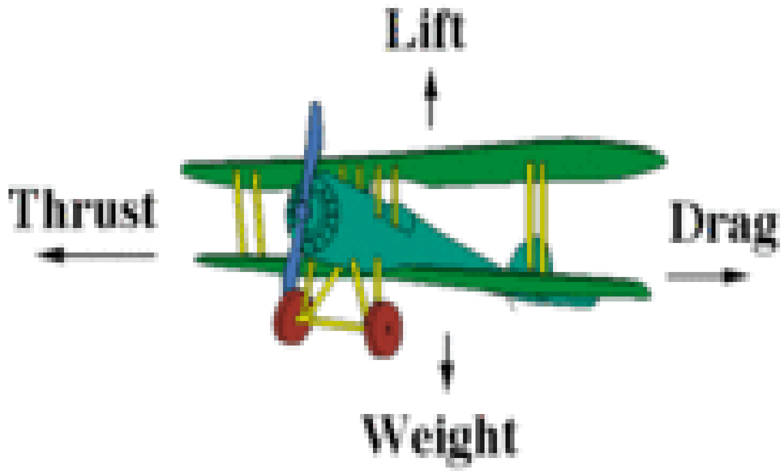
Real Flight

- Real flight is a balancing act between two sets of forces
  - Lift - weight
  - Thrust – drag
- It is also a balance between three possible torques.
  - Yaw
  - Pitch
  - Roll
- Achieving a stable balance between torques is vital for normal aircraft flight.
- This is usually achieved using a combination of rudder, tail-plane and wing control surfaces. A major problem is that, together with the fuselage, these surfaces increase overall drag so extra thrust is required



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But we are not dealing with aircraft!

- The objects we are discussing have no internally provided thrust and in general have a symmetry axis perpendicular to their major plane. The symmetry, if not circular, is almost so.

- Because of the lack of rudders and other control surfaces alternative mechanisms are needed to provide stability.

- From the shape and the means of external propulsion it is relatively easy to give the objects spin about the axis of symmetry

- Does spin provide an alternative form of stability?

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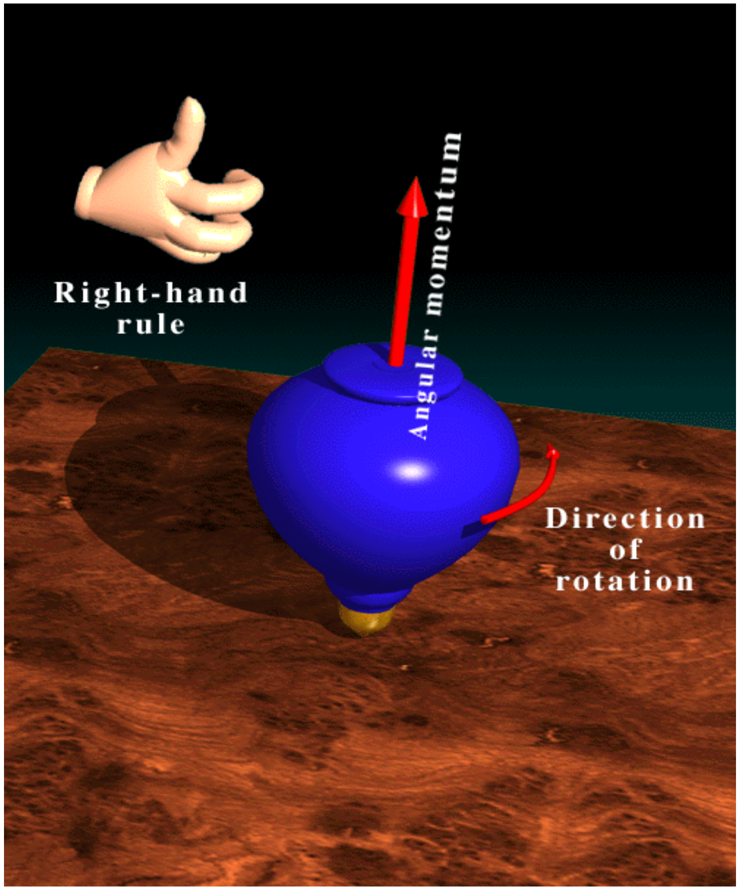
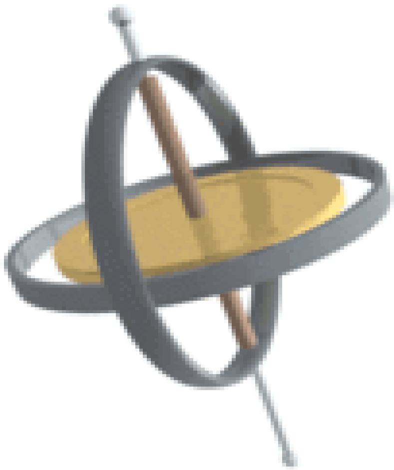
Stability implicit in rotating devices

- The simple answer is yes !!
- To see this we have only to look at the characteristic behaviour of a top (or what is sometimes referred to as a gyroscope).
- We have seen that, if no torques act on a spinning body, then its angular momentum is conserved
- If a torque acts on a body then by Newton's second law the angular momentum must change. If the torque is produced by a linear force then the torque is directed perpendicular to the plane containing the force and the principal axis of rotation.



Tops and gyroscopes

- One of the simplest examples is to look at a gyroscope to see what can happen.
- In general, if the principle axis is not parallel to the gravitational field, the gyroscope is subject to a torque perpendicular to gravity and the radius vector from centre of mass to the major axis of rotation.
- As will be demonstrated this produces a precession about the major axis and a ‘nutation’ perpendicular to the precession.
- The important point to note is that because of its high angular momentum the gyroscope exhibits stable behaviour i.e. it does not fall under gravity like a non spinning object would do.



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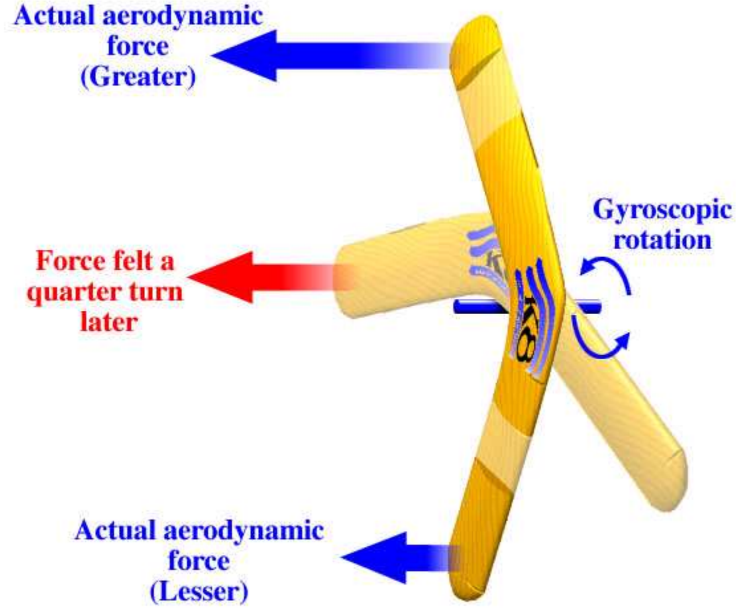
Boomerangs

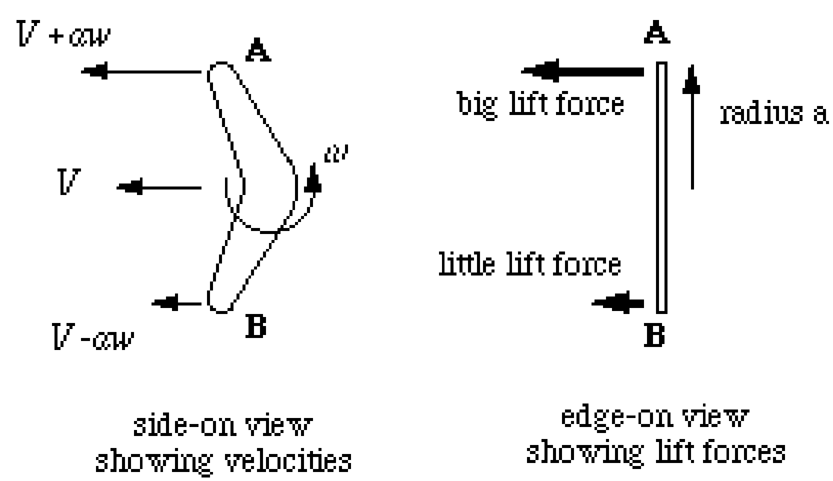
- Let us now move on to the problem of the flight of a boomerang.

- Let us assume a boomerang is rotating initially in the vertical plane.



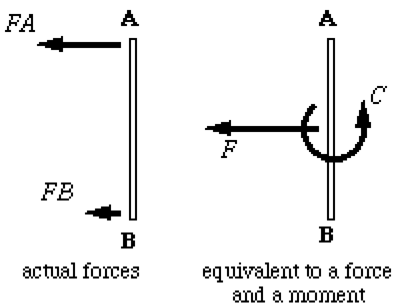
Boomerangs

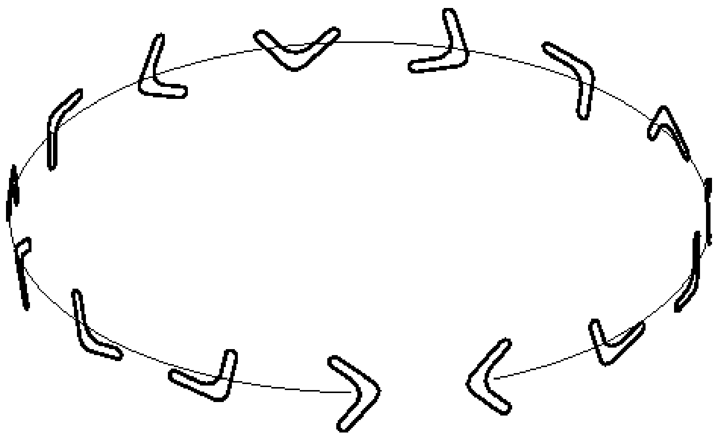
- Clearly as the disc has its major angular momentum perpendicular to its major plane the forward rotating blade has a higher speed than the backward moving blade.
- Hence, there is an imbalance of lift across the device hence a torque is produced perpendicular to the axis of rotation.



Boomerangs

- This means that there is always a force directed in the direction of rotation and a torque which changes the plane of the rotation.
- Hence ideally the boomerang moves on a circular path with its plane rotated.
- As the launch point is on the path, if the right amount of spin is given to it so that drag does not curtail the flight, it should return to the sender!!





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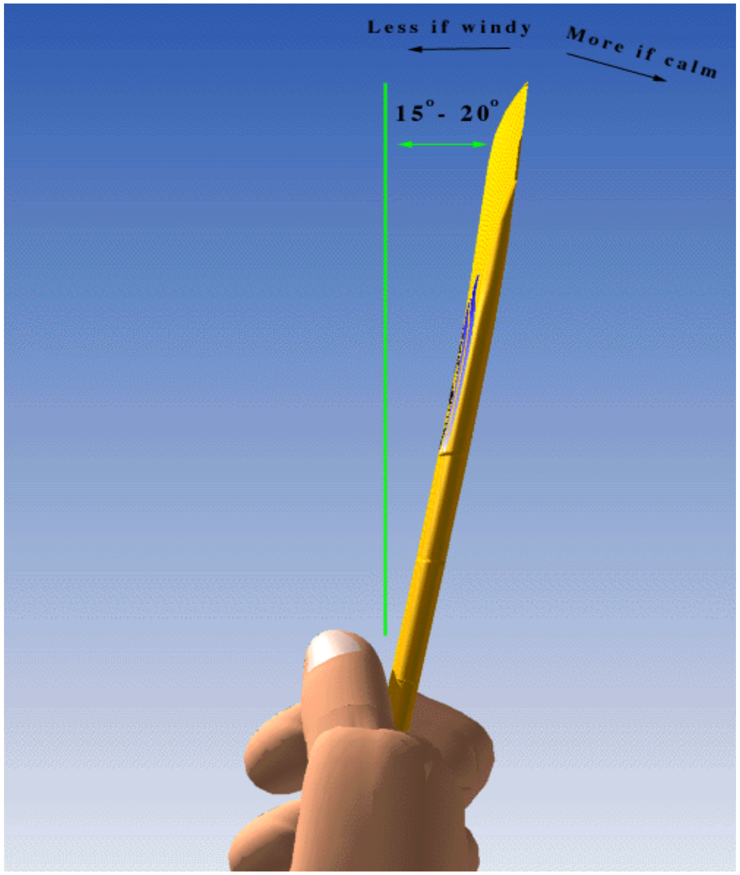
Boomerangs

- In practice throwing the conventional boomerang has to take into account the wind.
- Because the centre of mass of a conventional boomerang is not located at the centre of lift, care also has to be taken over the release. It is very easy to ‘stall’ one of the blades.



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Conclusions

- Simplistically the flight of a boomerang is the combination of aerodynamic forces producing lift which in turn interacts with forces tending to maintain the angular momentum of a spinning object.

- However the details of a given flight need a deep knowledge/understanding of the behaviour of fluid interaction with solid surfaces and the microscopic behaviour of the fluid itself.

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