WJEC CBAC

GCE A level

1325/01-B

PHYSICS

ASSESSMENT UNIT PH5

A.M. THURSDAY, 20 June 2013

CASE STUDY FOR USE WITH SECTION B

Examination copy
To be given out at the start of the examination.
The pre-release copy must not be used.

1325 01B001

Paragraph

From Newton, through Bernoulli to Super Jumbos – an explanation of lift

Let's define some forces first. Air flowing past a body exerts forces on it. **Lift** is the force that is
perpendicular to the flow direction and **drag** is the force parallel to the flow direction. Other forces 1
that act are **weight** and **thrust**. The thrust on an aeroplane is provided by the propellers or jets but
this force is absent for gliders.

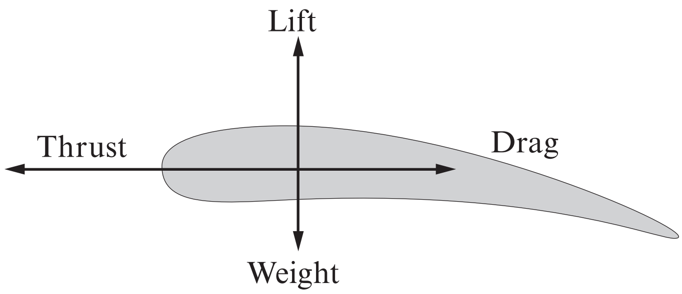


Diagram 1: Forces on an aerofoil

Lift is commonly associated with wings
but lift is also generated by propellers,
kites, helicopter rotors, rudders, sails on
sailboats, hydrofoils, wings on racing
cars, wind turbines and other objects.
While the common meaning of the word
"lift" assumes that lift opposes gravity, 2
lift in its technical sense can be in any
direction since it is defined with respect
to the direction of flow rather than the
direction of gravity. When an aircraft is
flying straight and level, the lift opposes
the weight. However, when an aircraft is climbing, descending, or banking in a turn, for example,
the lift is tilted with respect to the vertical. Lift may also be entirely downwards in some aerobatic
manoeuvres, or on the spoiler of a racing car. Lift may also be horizontal, for instance on the sail
on a sailing boat.

Newton's laws: lift and the deflection of the flow

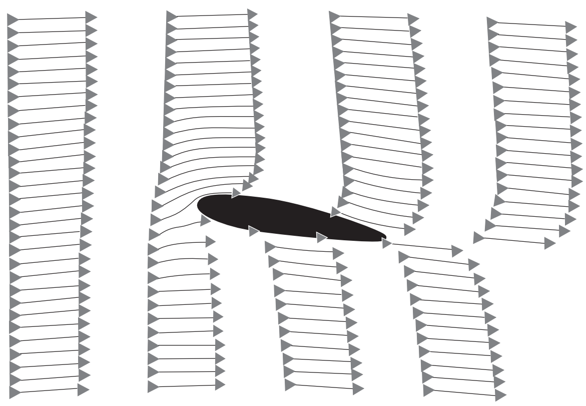


Diagram 2: Vector diagram of flow past an aerofoil

Flow of air around an aerofoil in a wind
tunnel. Note the curved streamlines above
and below the foil, and the overall downward
deflection of the air. One way to understand
the generation of lift is to observe that the air
is deflected as it passes the aerofoil. Since the
foil must exert a force on the air to change its
direction, the air must exert a force of equal
magnitude but opposite direction on the foil. 3
In the case of an aeroplane wing, the wing
exerts a downward force on the air and the
air exerts an upward force on the wing. This
explanation relies on the second and third
of Newton's laws of motion: *The net force
on an object is equal to its rate of momentum
change*, and: *To every action there is an equal
and opposite reaction.*

Pressure differences

Lift may also be described in terms of air pressure. Wherever there is a net force there is also a
pressure difference, thus deflection of the flow indicates the presence of a net force and a pressure 4
difference. This pressure difference implies the average pressure on the upper surface of the wing is
lower than the average pressure on the underside.

Bernoulli's Equation

In much the same way as the laws of electricity can be derived from conservation of charge and energy, the theories of aerodynamics can be derived from conservation of mass and energy. Let's consider conservation of mass first but we also have to make a couple of assumptions: 5

1. The density of the air is a constant (it turns out that this is a very good approximation as long as speeds remain below about 250 mph).

2. We consider a steady flow so that the air is moving along in steady streamlines.

Now let's consider streamlines that are getting closer together in this narrowing tube of starting cross-sectional area A_1 and finishing cross-sectional area A_2. 6

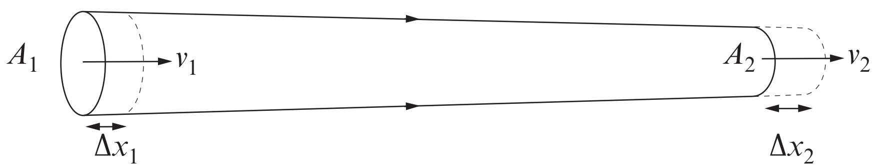


Diagram 3: Air flow in a streamline

The streamlines follow the path of the air so that (by definition) no air crosses the streamlines. The volume of air entering the tube in time Δt is

$$A_1\Delta x_1 = A_1 v_1 \Delta t$$

and the volume of air leaving the tube in time Δt is

$$A_2\Delta x_2 = A_2 v_2 \Delta t$$

Because the density is a constant, mass is proportional to volume and conservation of mass now means conservation of volume. So:

$$A_1 v_1 \Delta t = A_2\, v_2 \Delta t \qquad \text{or} \qquad A_1 v_1 = A_2 v_2$$

As the area decreases from left to right then the velocity must increase due to conservation of mass.

You can go even further than this, if the velocity is increasing from left to right then we have an acceleration and there must be a net force. The only thing that can supply this net force is a greater pressure on the left side of the tube than on the right. This would suggest that the pressure must be higher on the left side where the speed of the air is lower. Bernoulli's equation can be derived using this concept and the result is this: 7

$$p = p_0 - \tfrac{1}{2}\rho v^2$$

where p is the pressure, p_0 is the pressure of air that isn't moving, ρ is the density of air and v is the speed of the air. Basically, Bernoulli's equation says that the pressure of air that is moving is decreased by an amount $\frac{1}{2}\rho v^2$.

There are many things that can be explained using Bernoulli's equation but here's a little 8
explanation of one of the most annoying aerodynamic effects of all. Consider a person taking a shower with a light shower curtain. Which way does the shower curtain move?

To use Bernoulli's equation you need some idea of the speed of the air. Outside the shower, the air should be stationary (unless you live in a draughty house) but inside the shower, the water
droplets are causing the air to move slightly. According to Bernoulli's equation, the pressure inside 9
the shower will be lower so that the net force on the shower curtain is inward. There you are - an explanation of why that irritating cold and wet shower curtain always creeps spookily inwards towards you.

Explaining lift using Bernoulli

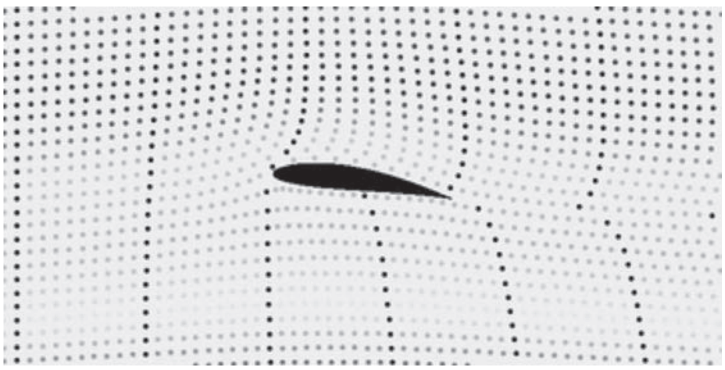


Diagram 4: Flow past an aerofoil showing time intervals

The diagram to the left represents the same flow past a wing as the previous vector diagram (diagram 2). The horizontal gaps between the dots in the diagram represent equal intervals of time. Note that the spaces between
the dark dots are much bigger at the 10
upper surface than at the lower surface. This means that the speed of the flow is far greater over the top of the wing than over the bottom. Hence, applying Bernoulli's equation explains why the above wing experiences lift.

Diagram 4 is great for explaining lift using Bernoulli's equation but it also debunks the old explanation of lift which went like this:

- when the air splits to go above and below the wing, the air passing above the wing takes 11
exactly the same time to reach the back of the wing as the air passing underneath,
- the top side of the wing is designed to be longer than the bottom,
- so air travels quicker over the top of the wing,
- Bernoulli explains why the pressure below is bigger than above and hence lift.

One look at diagram 4 should dismiss the first point of the old argument. Also, if the old 12
explanation was complete:

1. how can an aeroplane fly when the top of the wing is only 2% longer than the bottom?
2. how can an aeroplane fly upside down?

To get an idea of the first point, an Airbus super jumbo takes off at a speed of $80\,\mathrm{m\,s^{-1}}$ in air of density $1.2\,\mathrm{kg\,m^{-3}}$. Its wings are made in Broughton, North Wales and have an enormous area of
around $850\,\mathrm{m^2}$. If you assume that the speed over the top of the wing is 2% larger, this gives a total 13
lift force of 130 kN. This may sound impressive until you realise that the mass of an empty super jumbo is around 300 tonnes. The truth is that although the top side of the wing is only 2% longer than the bottom, the increase in speed can be more than 50% over the top side of the wing.

The second point is answered by considering the angle of attack (θ) of the wing because this is also 14
important in deflecting the airflow.

Lift due to an angle of attack

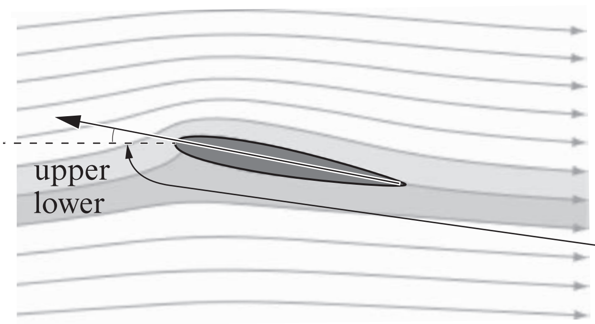


Diagram 5

The aerofoil shown to the left is symmetrical – the top and bottom of the aerofoil are the same (the wings of aerobatic planes are designed to be like this so that they 15
fly equally well upside down). In order to produce lift, the wings have to be tilted to produce the same flow as in diagrams 2 & 4.

An aeroplane flying upside down can still have an angle of attack and produce lift. 16

Lift coefficient

The lift force provided by a wing can be calculated as a function of speed with the following equation: 17

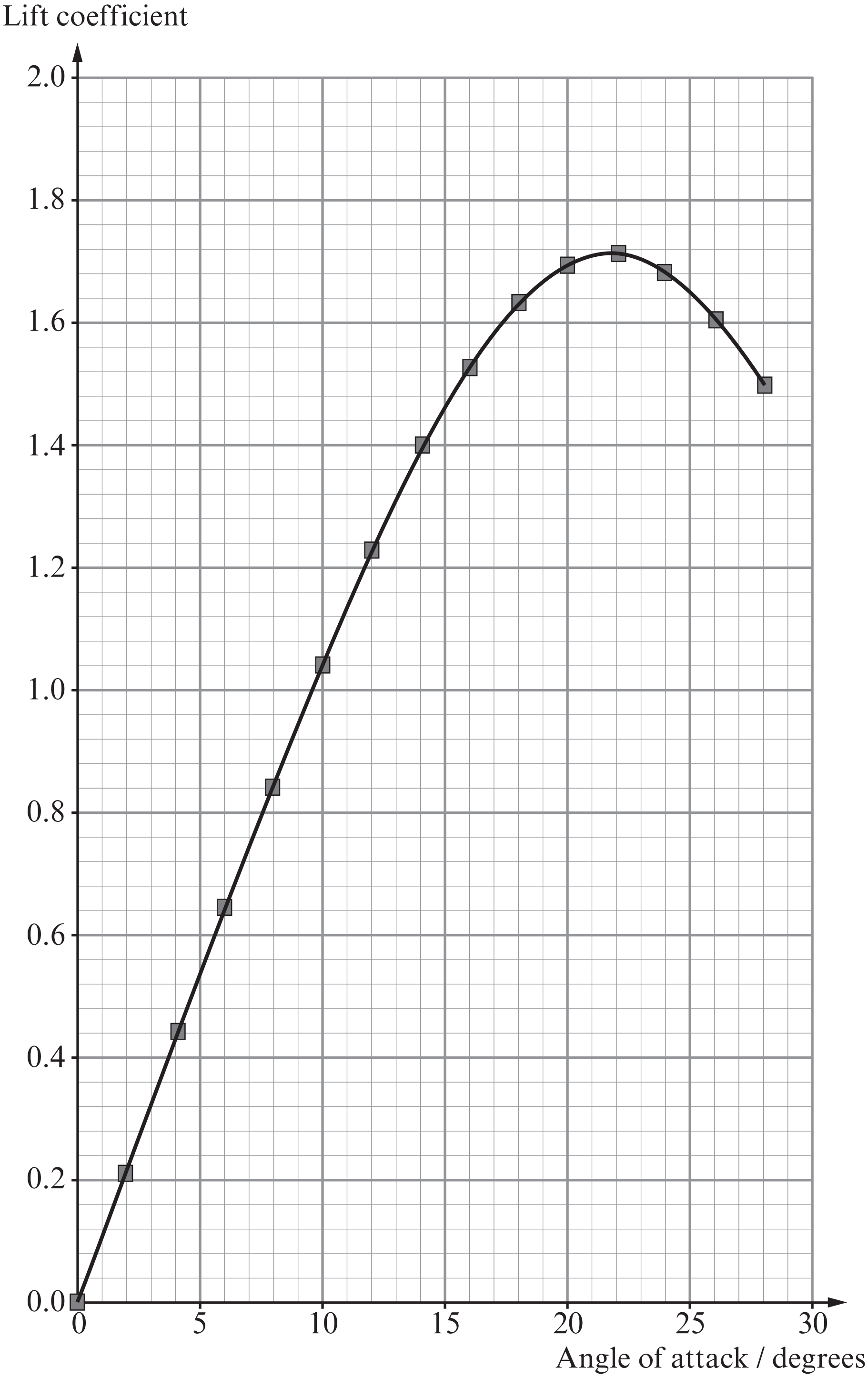
$$L = \frac{1}{2}\rho v^2 A C_L$$

where

- L is lift force,
- ρ is air density,
- v is air speed,
- A is the area of the wing, and
- C_L is the lift coefficient of the wing (dependent on the angle of attack).

This theory works very well and a standard experiment is to measure the lift coefficient as a function of angle of attack. In practice, real wings would be tested in extremely expensive wind tunnels but you could set up a cheap version of the experiment in a school lab using a thin metal 18
plate as a makeshift aerofoil. You'd also need a hair dryer, stand, clamp, protractor and a digital balance.

You won't be able to get such good data with a makeshift set-up because of the accuracy of your protractor and it's unlikely that a cheap hairdryer will produce
a particularly uniform 19
airflow. However, you should be able to measure the lift very accurately using the digital scales and the general trend of the graph shown should be measurable.



Conclusions

There are many aspects of the physics of lift and flight that are accessible to you as A-level physics students. It's surprising how far you can get just with Newton's laws of motion but applying these laws to obtain Bernoulli's equation leads to a far greater understanding of lift and fluid dynamics in general. You should now be able to explain how an aeroplane can fly upside
down and even perform a 20
rough experiment to show that your explanation is valid. You can even tell your friends what the likely pressure difference is between the top and bottom surface of an Airbus super jumbo wing.