Kinetic theory and drag (and Pooh Sticks)

Elsewhere is my article about kinetic theory and lift. Since publishing it I have had an email conversation with Philip Randolph Patten, about drag (not Lily Savage). He sent me his excellent paper about the subject, which triggered a need to write my own. To read the full, and very thorough, paper go to:
https://b2streamlines.com/Preprints/20200825NewtonDrag.pdf

Kinetic theory

For those who did not read my first article here is a summary.

All gases are made up of tiny molecules, which we can call particles. At sea level the volume of the particles is about one thousandth of the volume of the gas. They move at random, on average at the speed of sound. They bounce off each other and solid objects. The hotter the gas the faster the particles move. Gases store heat energy in the form of this kinetic energy which increases with the square of their average speeds. The particles do not stick to each other but adhere a little to a solid surface. Hence the boundary layer on a wing. They bounce perfectly elastically, so no energy is lost that way.

Drag is a mechanical force. As we are dealing with physical matter, it should be possible to explain drag in terms of molecular motion as Isaac Newton did. Newton was fond of particles. He also said that light was particles, which made everyone fall about laughing until the discovery of photons.

Newton showed that force is the result of a change in momentum. Momentum is mass times velocity mv. When a particle bounces off a solid boundary it imposes an impulse on it. An impulse, according to Newton, is a change in momentum and is equal to force times the time of contact. Newton's equation therefore is impulse Ft = mv. Divide through by t. As v/t is acceleration we get to the modern version of Newton's Second Law which is F = ma. Forces, like all vectors, can be resolved into two (or three) components at right angles to each other.

What is drag?

When a solid object moves through a fluid - a liquid or a gas - or a fluid moves around a stationary solid object - the object experiences a force called drag. For a moving object this opposes the movement. In powered aircraft, the engine must produce a forward thrust as big as the drag to maintain a steady airspeed in level flight. A glider must tilt its nose downwards so a small component of its weight pushes it forward through the air to generate lift. The less drag the glider has the less this tilt, called the glide angle, needs to be and the further it can travel from a given height. For high performance gliders it can be as high as 1 in 40. For a Bixler 3 it is around 1 in 6 in still air (a Bix3 glides at about 12 knots or 6 ms^{-1} and sinks about 10 m in 10 s, both measured by me using FrSky telemetry).

How can particles create drag?

What follows only applies to gases, in other words aerodynamic drag. Liquids have other drag inducing effects. Philip's paper includes liquid drag which is why I wanted to write my own.

In wind tunnels, airflow is modelled using streams of smoke, or with bits of cotton, called tufts, glued at one end to the objects.The lines are called streamlines and show how the air flows round objects. They are not real lines, any more than the field lines drawn round a magnet. They are just models to help us think. The lines in figs 1 and 2 are streams of smoke.

These are pictures taken in wind tunnels.

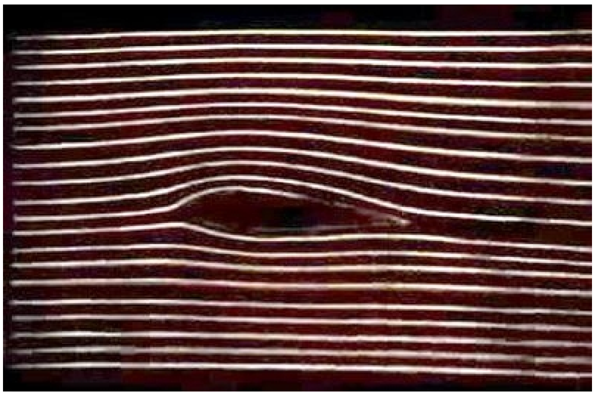

Fig 1

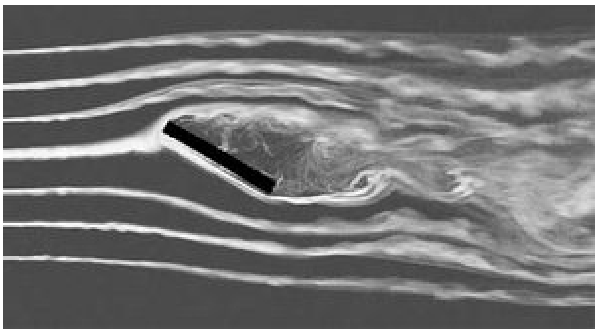

Fig 2

Fig 3 is the classic set of diagrams to illustrate flow and drag. Intuitively you can see why a flat plate at right-angles to the flow will experience the most drag. But hold on a minute! At no point does the air in the pictures actually touch the objects, only flowing round them. How then can it impose a force on them? The only force would be from the viscosity of the air which is low.The percentages are relative drag compared with the plate at the bottom.

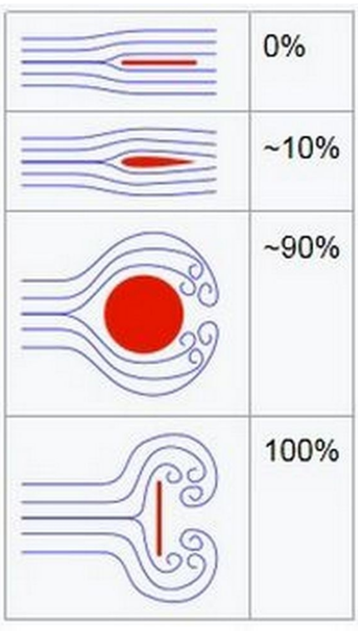

Fig 3

Notice that the frontal area is the most important. The sphere experiences little less drag than the plate despite its curved shape. The wider the object the more air particles it collides with. Patten quotes from Newton's Principia book '…the resistance…arises from the inertia of matter…' Inertia is mass, which is part of momentum.

Let us examine how particles impose the forces

Fig 4 shows an air particle, which is itself moving, colliding with a moving plate at right angles. As its motion and momentum is reversed it imposes an impulse (momentary force) on the plate. Because it collides at right angles all of the impulse opposes the motion of the plate. The sum of all impulses are a major part of the drag.

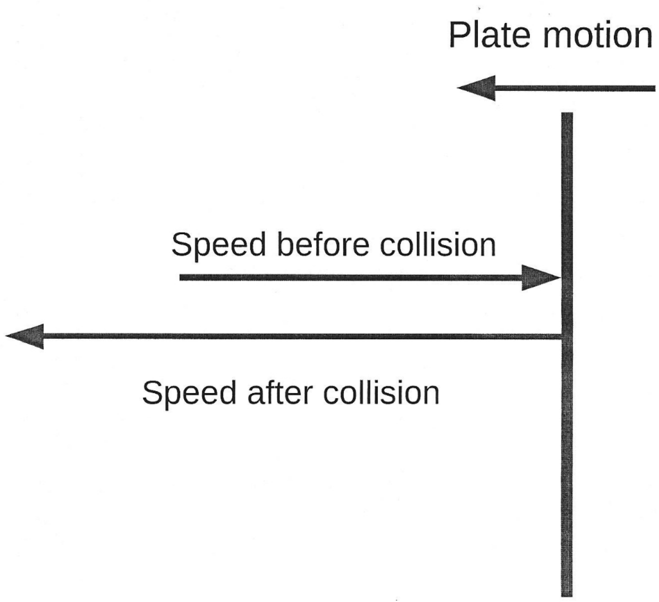

Fig 4

Where a surface is curved, as in fig 5, the situation is more complicated. The particles at, or near to, path A give impulses similar to those on the plate above. Those in path C bounce at a shallow angle so only a small part, or component, of the impulse force acts in the direction of motion. Thus it makes only a small addition to the drag, Path B is somewhere in between. Again, adding up the components of all the impulses in the direction of the motion are a major part of the drag.

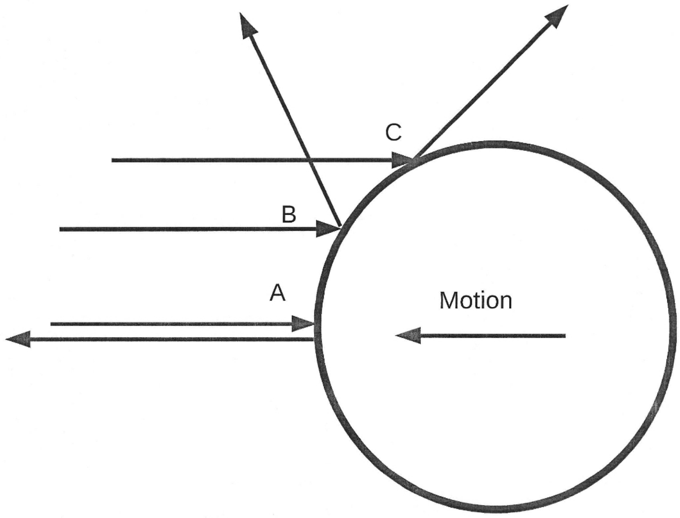

Fig 5

Aerofoils

These comprise a mix of curves. Some aerofoils are similar to the horizontal plate in the table above. These are the ones designed for high speed in, for example, the English Electric Lightning and the Lockheed F-104 Starfighter. Here the impulses are just on the front surface, which is tiny, and on the slight curvature. Of course drag isn't 0% on the wings as shown in the table.

Most aerofoils have a significant frontal area. Fig 6 is an example.

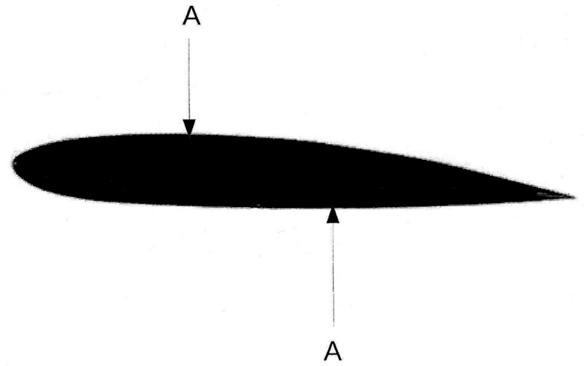

Fig 6

The arrows A point to where the wing surface is parallel to the airflow so can no longer experience a drag component from the impulses. The A for the lower surface is further back because of the tilt of the aerofoil due to the angle of attack.

Applying the ideas from the sphere you will now be able to see how the impulses push on the aerofoil to a greater or lesser degree depending on the angle at which they hit the surface.

The nature of the aircraft's surfaces will also affect drag. Anything that has a projection facing the air flow will increase drag, for example proud rivets, control surface actuators and air brakes. Howard Hughes increased the speed of his H-1 Racer by getting his builders to grind the rivet heads off flat. That was just before he had his spectacular crash flying it. One of the reasons for the speed of the DH Mosquito was the smoothness of its wood surfaces. I wonder how much speed was lost due to the tail wheel that didn't fully retract.

Another source of drag

There is also drag due to air viscosity. This applies all over the aerofoil including behind the points A. The viscosity of air is about fifty times smaller than water. James Clerk Maxwell and his wife did the first experimental study of gas viscosity around 1860 by measuring flow through capillary tubes. These of course have very narrow bores. Aircraft are surrounded by relatively 'free' air so we might expect viscous effects to be less. The Maxwells' work assumed that fluids flow in layers, each called a lamina. The 'friction' between the laminae is what causes viscosity. Remember this is only a simple model. The reality will be more complicated. A model is only useful whilst it matches reality. Perhaps the notions of layers and gas viscosity are an unnecessary complication?

The stationary gas layer next to a solid surface is stuck to it by adhesion and is called the boundary layer. In fluid flow in general, as you move away from the solid surface, successive layers move faster until you reach the fluid moving at full speed as shown in fig 7. You can see this clearly in liquids. It is after all how you win at Pooh Sticks. You must throw your stick into the centre of the stream as it goes under the bridge, not the edge where the flow is less.

The picture is only true for laminar flow, which is where each lamina layer does not mix with its neighbours. At a certain speed however the layers start to mix, an effect we call turbulence. Going back to Pooh Sticks, it is best to use a slow flowing stream. In faster ones there will be visible turbulence making it more difficult to win. Fig 2 shows turbulence forming on a stalled plate.

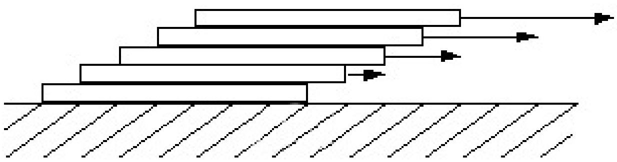

Fig 7

Viscosity, though measurable, is an abstract notion. What I wanted to do was to explain viscous drag in gases using particle impulses. Unlike liquids, gas particles have no cohesion, a word that means forces holding them together. There is a small attraction effect, one of the so-called van der Waals forces. These are very small and only apply when the particles are very close.

Thought experiments

Einstein and others used thought experiments to imagine puzzling phenomena. Newton explained how the moon stays up by imagining firing a cannon ball more and more powerfully until it was going so fast it never fell to earth, but just went round in a circle. Einstein came up with special relativity by imagining he was riding on a beam of light. He asked what would the world look like to the light beam? Weird, but instructive, was the answer.

Can we do the same for air viscosity? I imagined myself as an air particle in the boundary layer of a moving surface. I am sort of attached to the surface but I am not still. I am vibrating and faster air particles are flying by. They do not move in straight lines but are moving at random within a kind of moving sphere and colliding with other particles. I don't duck quickly enough and one whacks into me. It's not hard enough to dislodge me but it makes me vibrate more, so my temperature goes up a little as I absorb some kinetic energy. The other particle slows a little, not only in its random motion but also linearly. I act as a drag on this particle and all the others near to it. Wey hey, there's the word - drag. I notice that this particle also collides with others further out as they go past, so the effect is a speed gradient just as shown in fig 7. And the great bonus of this is that we don't need to use notions like viscosity. It's all in the particle movement and collisions, just as Newton suggested using the term 'shear friction'.

How can we explain turbulence?

At the moment I am still attached to the surface. However the surface is speeding up so the nearby particles are going faster and faster. In the end one whacks me so hard that I can no longer stay attached to the surface. Nor can my neighbours, so we all swirl around at random. Can it really be that simple? Reynolds created a simple equation in the 1880's that produces the Reynolds Number that defines the speed at which a fluid will become turbulent.

A summary

Drag due to frontal area and to the relative motions of particles running parallel to a surface can both be explained solely by particle motion and collisions. As a bonus we can see how turbulence occurs at a critical speed defined by the Reynolds Number. Please pick holes in these ideas and let me know where I have gone wrong.

Turbulence naturally occurs on wings usually in the rear half of the chord. The resulting draggy 'bubbles' can be kept under control by turbulators. In my article on lift I asked whether the action of turbulators could be explained using these ideas. I haven't cracked that one yet nor has anyone else suggested an answer. However I have found several research papers and other sources that will I hope clear the fog from my brain. Here they are if you want to inquire yourselves:

https://repository.lib.ncsu.edu/bitstream/handle/1840.16/1711/etd.pdf?sequence=1&isAllowed=y

https://www.researchgate.net/publication/269204821

http://www.physicsdemos.juliantrubin.com/encyclopedia/aviation/boundary_layer.html

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