We do Actually Know How Planes Fly

Ayden Bennett

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1 TLDR

In one paragraph this is what lift is: The flow gets turned and sped up as it moves around the airfoil which in turn increases its downward momentum. By Newton's third law this creates a force on the airfoil in the opposite direction. This simply creates a difference pressures from the top to the bottom of the airfoil as a result of Newton's second law of motion and conservation of mass which predicts that a pressure change accompanies a change in air momentum. This is Bernoulli's principle. Both Newton's third law and Bernoulli's equation happen simultaneously and for an engineer, either can be used to compute lift as soon as the governing equations (Navier-Stokes, which is derived form Newton's second law) are solved. Whether you sum the pressure in the perpendicular direction to flow (using Bernoulli's principle) or compute the total change in momentum of the air moving past the airfoil (Newton's third law), you will get the same answer. Lift is not a mystery, it is merely the laws of physics.

2 Introduction

To my reader, I am making this because I constantly am finding people across social media platforms stating that we don't know exactly how planes fly. I am writing to clarify some of this misunderstanding. Maybe this is petty of me, but it bothers me that people think we don't understand lift. We do! It is true that there are holes in our understanding of fluid dynamics (i.e., the best way to model turbulence that is computationally feasible), but we have a pretty dang good idea of how lift works. I have spent a considerable amount of time doing aerodynamic analysis for all sorts of airfoils helping out grad students for my job (undergrad researcher). I have written two inviscid potential flow solvers using two different methods (Hess-Smith method and Martensen's method). If you are curious, a potential flow solver will compute lift for an airfoil using some assumptions to the governing equations of fluid dynamics (Navier-Stokes equations). With these assumptions we can get pretty dang good predictions for lift from an airfoil.That is up until a certain point, of course....(aka stall)

Want to see just how accurate a potential solver can be? Figure 1 is a great example. The blue line represents actual experimental data from the

National Advisory Committee for Aeronautics (NACA) Abbott et al. (1945). This particular airfoil is the very well-studied NACA-2412. The red line is data I obtained using a mathematical solution with a potential solver (Martensen's method in particular) Lewis (1991). You will notice how with this airfoil (NACA 2412) - the points line up extremely well, but as you approach stall (more on this later) they start to be quite different! This is because these kinds of solver usually don't predict stall which occurs from flow separation. Alright, enough with showing off, let us talk about how planes actually fly!

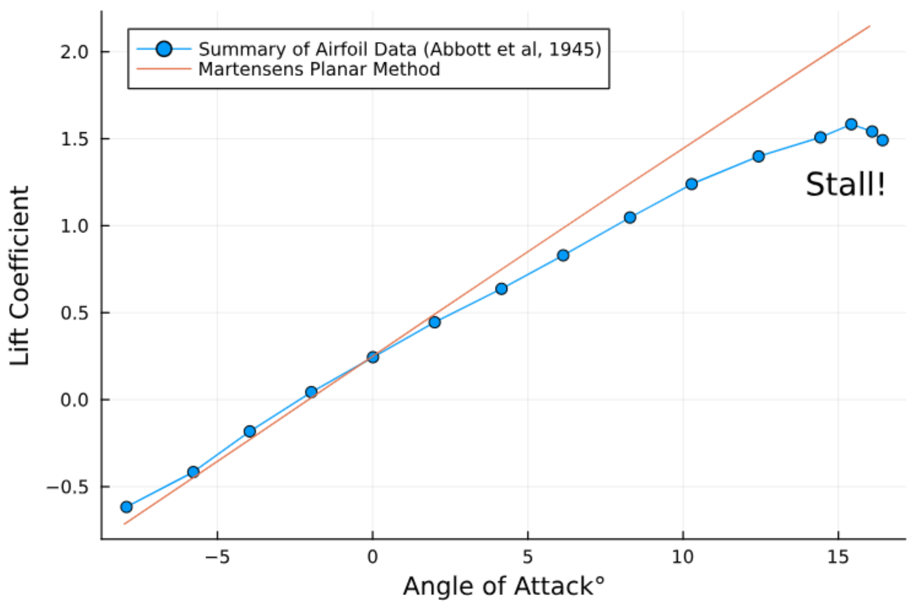

Figure 1: Lift Coefficient For A NACA 2412 Airfoil

3 Bernoulli or Newtons 3rd Law?

Short answer, both as well as Newton's 2nd law and conservation of mass. But let's dive into these principles. Newton's 3rd law is really simple: for every action there is an equal and opposite reaction. Basically, when you push air down-it pushes up on you. An airfoil essentially redirects the air slightly downward through viscous forces (see nomenclature). Essentially, the air sticks to the airfoil as it passes, which creates a thin layer of air we engineers like to call a boundary layer. This layer spreads as the flow progresses along the airfoil. The result is that the flow will follow the contour of the airfoil as long as the flow does not separate (which creates that stall we talked about before). Here look at figure's 2 and 3 (disclosure I totally made these using Microsoft paint and PowerPoint so bear with me).

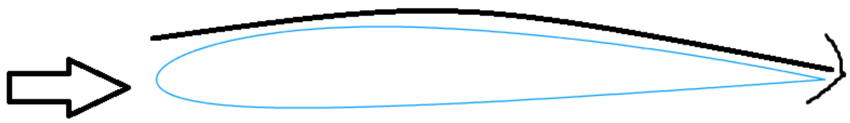

Figure 2: Flow being redirected downwards from camber - Big arrow on left shows oncoming flow

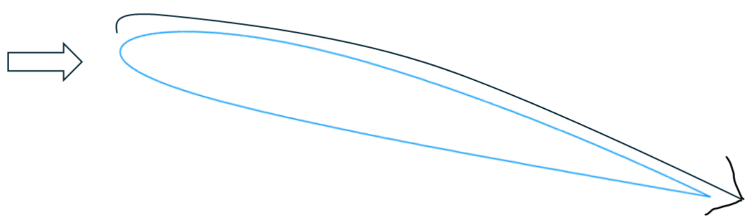

Figure 3: Flow being redirected downwards from a positive angle of attack

Well..what happens at the trailing edge of the airfoil? If the flow doesn't separate it comes off the trailing edge smoothly, which we engineers call the Kutta condition. This is what potential solvers are using to solve the governing equations (Newton's 2nd law and conservation of mass). They are assuming that the flow doesn't separate as well as a couple other assumptions that makes the equations of motion actually solvable analytically (inviscid, irrotational, incompressible, steady). Which you may be wondering: wait a minute! You said that viscosity causes the flow to stay bounded to the airfoil. Indeed I did.

The cool thing about these equations is we can incorporate this viscous effect by enforcing a mathematical definition of the Kutta condition at the trailing edge. In reality, this is an approximation, but it actually works really well for many airfoils. Anyways, let's move on to the result of this phenomenon. Notice in figures 2 and 3 that the resultant flow is pointing downwards? The airfoil is forcing the air downwards which pushes the plane up. This is that downwash that pilots will talk about. This change in velocity of the fluid (ie velocity is pointed downwards) means that we are changing the momentum of the air which is why there is a lift force on the wing of the plane.

So what about when the flow separates? Well, when that happens that downward arrow is more horizontal than vertical which will mean that the air doesn't get pushed down as much. This is why we lose lift. Probably even more important than this loss of lift is a HUGE increase in drag. The aircraft will rapidly lose airspeed at stall which can be really dangerous!

So what about Bernoulli? Isn't there a higher pressure at the bottom than at the top of the airfoil? This is the exact reason I wanted to write this paper in the first place and I hope what I'm about to say blows your mind. Guess what, pressure will adjust according to the change of momentum of the air. What do I mean by that exactly?

You first have to understand that pressure and velocity in fluid dynamics come paired. They influence each other throughout the flow. When you change velocity, you'll often change the pressure and vice-versa. So when the flow changes direction, it is accompanied by a loss of pressure on the top surface of the airfoil. Also important to note is that as the fluid moves around the the airfoil it will also speed up as it gets "slung" around or accelerated around the curvature of the airfoil. There is also some squeezing of the flow as it rounds the leading edge of the airfoil which causes that increase in velocity (due to conservation of mass). This adds to the downward speed of the fluid as it exits the airfoil. This is precisely where Bernoulli's equation comes into play.

4 Bernoulli's Equation

Bernoulli's equation is actually pretty cool. If you think about it, it's really just an energy balance. Basically, it states that your potential energy plus your kinetic energy must remain the same across layers of the flow we like to call streamlines. This assumes no energy loss to things like friction which is reasonably true for flow along the airfoil (not very true behind the airfoil because the flow gets pretty turbulent and lots of energy gets dissipated).

Basically if you have a flow that doesn't have any work done on it the energy has to remain the same. So when you have a flow that speeds up (increase in kinetic energy) you have to have a loss in pressure (decrease in potential energy) for the amount of energy in that fluid layer to remain the same or vice versa. This principle explains a lot of phenomenon, but few people understand that it was actually derived using a sum of forces equation (Newton's second law: F = ma). I won't go through all the math and details, but if you were to sum all the forces that act on the fluid layer (in the direction of the flow) and multiply them by the distance that fluid layer goes then you'll get the total energy of the layer. This amount of energy remains constant from point 1 to point 2 which yields Bernoulli's famous equation Gerhart et al. (2016):

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{1}$$

If you were to apply this exact same technique to bends in a flow, you will find that if you sum the forces in the opposite direction of the flow, you'll get this handy dandy equation Gerhart et al. (2016):

$$\frac{\partial P}{\partial n} = -\frac{\rho V^2}{R} \tag{2}$$

Basically, this equation just states that when a flow is turning the pressure drops according to how tight of a turn it is making. If you were to integrate this differential equation you would essentially create Bernoulli's for a turning fluid which is pretty neat!

That's all Bernoulli's equation is! It is just a manifestation of forces acting on a flow. It just turns Newtons second law into an energy equation which gives us a succinct way to compute pressure if we already know the path (streamline) of the flow. It does not, however predict the path of a flow nor does it predict velocity if neither velocity or pressure is known. This is why we can't just use Bernoulli's when explaining lift. It is a byproduct of Newton's 2nd law.

5 Conclusion

So, we just went over a lot of physics here and it still might not make sense how everything ties together. This is what I aim to do right now.

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