Paper Aeroplane Aerodynamics

Paper aeroplane aerodynamics vs normal plane aerodynamics

Paper aeroplanes are incredibly interesting; this project outlines some key areas of aerodynamics and aeroplane design that are pertinent to paper aeroplanes as well as how those areas also relate to real planes.

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Paper aeroplanes have fascinated people of all ages for a long time, the ability to make something fly so simply is appealing as it gives us the opportunity to explore the extraordinary world of aeroplanes. In this essay I will be discussing the aerodynamics of flight and how paper aeroplanes apply them in comparison with how 'normal' planes apply them. Also, I will document my experiments with applying these principles to creating a paper aeroplane that flies stably.

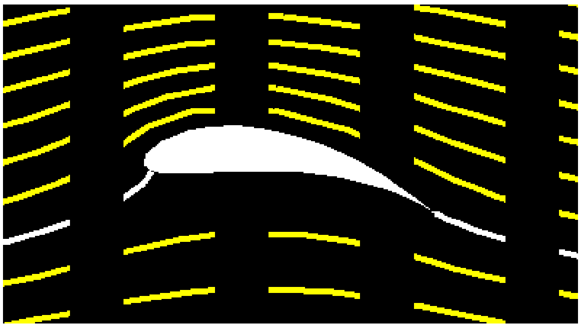
Lift

There are many different theories on how lift is generated[1][2]. Unfortunately, tend to be all found in many places and so distinguishing between correct and incorrect theories is difficult. The following theories are the most common or most credible theories that I could find.

Equal Transit Theory

Firstly, the 'equal transit theory'. This theory is based on the Bernoulli Effect (The Bernoulli Effect is the lowering of pressure in areas of high velocity in a fluid[5]), it states that since the top of the aerofoil (an aerofoil is a shape, usually curved, designed to generate lift) is longer, the air must go faster and so there is a lower pressure, thus generating lift[1][3]. The tricky part with this theory is that much of the science seems to make sense, the particles over the top of the wing will travel faster thus there will be lower pressure, but the mathematics behind the equal transit theory does not correctly predict the actual lift that is generated[3][4]. In fact, the flow over the top of the wing arrives at the trailing edge significantly before the flow under the bottom[1]. This means that the Equal Transit Theory does not predict enough lift based on the Bernoulli Effect.

The Coanda Effect



The Coanda effect is the tendency of a moving fluid to 'stick' to a surface[6]. A good example of this is putting a spoon near a running tap, the water will move towards the spoon. Similarly, airflow over a wing sticks to the wing. When the wing has a non-zero angle of attack (the angle the centre line of the aerofoil makes with the flow of the air) this effect causes the flow of air to turn. Since momentum must be conserved, the changed flow of the air causes the wing to go up[7] as the air is being moved down.

Conservation of Momentum

Another widely cited theory is that of conservation of momentum[8]. Similarly to the equal transit theory, this theory seems to make sense and is written about a lot. This theory states that air particles hitting the bottom of the wing will deflect and since every action has an equal and opposite reaction the wing must therefore be pushed up. However, due to the Coanda effect turning the particles, no particles actually hit the wing directly and so this theory is incorrect. The particle motion is similar to a car going around a corner; it follows the corner but doesn't hit the curb. This theory was one of the main problems I came across when researching lift theory. Many websites (including one from NASA) had cited this theory and it seemed to make sense. However, I found a different NASA website[9] that explained why it must be wrong. The author of the second article is more credible due to his expertise and, after emailing him regarding the issue, provided some of the information detailed above about why the conservation of momentum theory is wrong as well as some complex mathematical equations proving it[9].

Comparison of real vs. paper

Real planes use a variety of lift mechanisms (primarily the Bernoulli effect and the Coanda effect) and are carefully designed to make the most of all of them. There are still debates as to which mechanisms generate different proportions of the lift[10]. Paper aeroplanes predominantly generate lift using the Coanda effect, this is because the wing cannot have very much shape (this will be explained later) and so cannot use a shape that would generate extra lift through other mechanisms. This can pose issues because paper aeroplanes often have no tails to balance the upward force on the back of the wing, but this can be countered by elevators which create a downwards force to keep the plane from being unbalanced.

Stability

Fins

One feature of an aeroplane that can be used for stability is a pair of fins. These are similar to the vertical stabilizer at the back of a ‘real’ plane except smaller and on the end of the wings (real planes tend to use more complex versions of fins compared to paper aeroplanes). These can have a couple of effects.

Firstly, fins can give a plane lateral stability[11] (lateral stability means a plane doesn’t move around side to side), if a plane starts to wobble the fins can generate opposing sideways-lift that rotates the plane back into line (see Fig 2). If a plane didn’t have good lateral stability it would likely wobble during flight which can increase drag and cause it to go in unwanted directions or even crash.

Fins can move the centre of gravity simply by being there[11]. This mainly affects paper aeroplanes as the fins are a more significant proportion of the weight than on a ‘real’ aeroplane. If the fin is bent downwards it moves that mass lower than it would have been and allows the centre of mass to be more easily moved below the centre of lift.

Winglets (a more complexly designed version of fins) also affect the vortices (swirling flows of air) on the ends of wings, they can reduce drag and increase lift[12]. This is more advanced aerodynamics so I won’t go into it in depth.

Dihedral Wings

Aeroplane wings can be tilted to make the plane more stable. Wings tilted up are called ‘dihedral’ and wings tilted down are called ‘anhedral’. Dihedral wings make planes more stable, this is because when they are titled upwards the centre of lift is also moved upwards[11]. This is similar to a pencil. The centre of lift is like where you hold the pencil and the centre of mass is like the centre of mass of the pencil. If you hold the pencil at the top it stays nicely vertical, if you hold it at the bottom it falls over quickly. Similarly, having the centre of lift above the centre of mass keeps the plane upright. Most planes use dihedral wings because they make the plane more stable. The main exception to this is fighter planes; they often have anhedral wings to make them less stable and easier to maneuver quickly. However, this requires lots of computers to keep the plane stable in flight and so is impractical for most planes.

Having dihedral wings also allows for flight in conditions where the airflow is partially lateral, for example in environments where wind has an effect[11]. This only really matters for paper aeroplanes because they are much lighter and so can be blown around easily. The dihedral wings help because the lateral flow strikes the underside of a wing tilting it upwards and turning the aeroplane away from the wind or simply moving it sideways. If the wings were anhedral or simply straight, the wind could catch the top of the wing and force it downwards. This would keep the wings in the wind and the plane would flip over.

Comparison of real vs. paper

Stability is an issue that paper planes suffer from more than real planes in terms of design. Paper planes are a lot lighter and so things like wind have a lot more of an effect. Obviously, real planes suffer these same issues but they also have a much greater ability to be changed in small ways that fix issues with greater accuracy (millimeter precision on most parts of the aircraft as well as years of design).

Scale differences

The most obvious difference between a ‘real’ aeroplane and a paper aeroplane is the size. A paper aeroplane is obviously much smaller and this affects how it interacts with the air as well as the material requirements and wing shape.

Wing shape

Paper aeroplanes have many problems because they are in fact made of paper. Paper is a relatively flimsy material and so cannot be used effectively to make structures similar to ‘real’ planes. This massively restricts the shapes that paper aeroplanes can be. For example the aspect ratio of the wings (the ratio of its chord (breadth) to its length, where a high aspect ratio is long and thin and a low aspect ratio is short and stubby) has to be higher to stop the wings simply flopping around.

Texture

The texture of a surface can affect the airflow around it. A good example of this is a golf ball. The dimples in it allow it to fly more efficiently and so further[13]. Similarly, some aeroplanes use this to reduce drag and so fuel costs. However, not all shaped surfaces reduce drag, so often planes have smooth surfaces to minimize drag as much as possible. The choice between surfaces often depends on purpose and size of the aircraft. Typically paper aeroplanes will have smooth surfaces whereas normal aeroplanes may have more carefully designed surfaces.

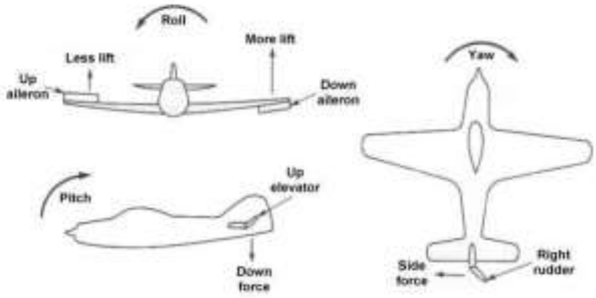
Wing Thickness

The ratio of momentum forces to viscous forces in a fluid is called its “Reynolds number”. To put it more simply, the higher the Reynolds number the less influential the viscosity of the fluid. Since the momentum is relatively low, a Reynolds number calculation that shows the Reynolds number of a paper aeroplane is approximately 37000. For comparison, the Reynolds number of a small ‘normal’ plane is about 6,000,000. The lower the Reynolds number the thinner the wings should be so that there is less turbulence around the wings. Since a paper aeroplane has a very low Reynolds number it must therefore have thing wings and thus very little shape to cope with airflow.[14]

Other features

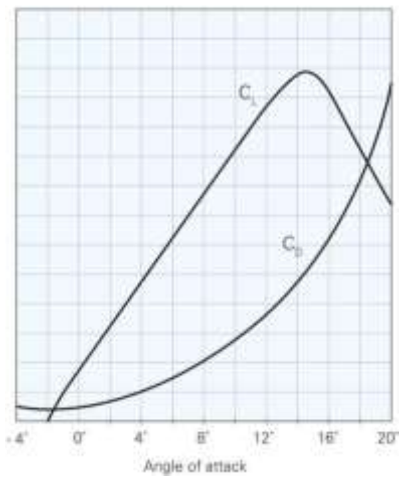
Control surfaces

Control surfaces (moving parts of the aircraft designed to change how it flies) work in the same way as wings. Moving the control surfaces causes more lift to be generated on one part of the plane than the other and thus makes the plane pitch, yaw or roll (see Fig 3 for explanations of these terms). For example, to make the plane yaw the rudder is moved. Normally the rudder is kept in line with the vertical stabilizer and so generates no horizontal lift. If the rudder is moved to the left the airflow sticks to it[9] and so shoots off to the left. This pushes the tail to the right and turns the plane around its centre of gravity, thus making the plane yaw to the left. The same happens with the elevators and ailerons (the control surfaces on the back of the plane and on the wings, see Fig 3). Control surfaces on 'normal' planes are used to change its course whereas on paper planes they are simply used to aid stability or change how it flies (loops, circles etc.).



Balance of forces

There are two main types of forces acting on a plane, the linear forces (normally simplifications of other forces), these can be mostly summarized as thrust, drag, lift and weight. The other main type is the rotational forces. These cause the plane to pitch, roll and yaw. To make a plane stable in flight all the forces should be balanced. Most planes are symmetrical so roll and yaw are almost always balanced. However, pitch can be a problem. The two forces affecting pitch are the lift and the weight. These act from the centre of lift and centre of gravity (or mass), respectively. If a plane has a centre of lift in front of the centre of mass then the plane will tend to pitch up, and if a plane has a centre of lift behind the centre of mass the plane will tend to pitch down. If the angle of attack of a plane is too high the drag increases massively, we call this 'stalling'[15]. Normally the centre of mass should be in front of the centre of lift so that if the plane stalls it will pitch down and recover speed and fly normally again. This is usually achieved by wing shape or wing placement. In a paper aeroplane, where it is hard to have wings in specific places, the wings are often 'swept' back (forming a triangular shape with the wide end at the back) so that there is less surface area at the front, thus the centre of lift is moved backwards[1].



Sources and Appendices

Images

Figure 1	http://www.grc.nasa.gov/WWW/k-12/airplane/right2.html	Picture showing the Coanda effect on a wing.
Figure 2	Created by me	A picture showing the effect of a skewed fin on lateral force.
Figure 3	http://www.aerospaceweb.org/question/dynamics/yaw/controls.jpg	Image showing the control surfaces of a plane.
Figure 4	http://www.caa.govt.nz/fig/images/AM-WDS-FIGURE-1.jpg	Graph showing the angle of attack against lift and drag.

Sources

Source number	Reference	Description	Analysis
1	"The New World Champion Paper Airplane Book", Ten Speed Press, 26 March 2013, John M Collins, Page 13	A book about paper aeroplane making, Page 13 includes a discussion about lift theory.	Author is world record breaking paper aeroplane designer and so is likely to be credible.
2	"A comparison of explanations of aerodynamic lifting force" Am.J.Phys 55, January 1987, Klaus Weltner, Page 52	An article discussing various theories of lift.	Published in the American Journal of Physics, AMJ is a very credible source due to their expertise.
3	www.grc.nasa.gov/www/k-12/airplane/wrong1.html	Page discussing why the Equal Transit Theory is incorrect.	Written by a NASA Aeronautics researcher, thus credible due to his expertise.
4	Sciencebasedlife.wordpress.com/2012/02/06/how-design-airplane-wing-generate-lift/ 02/10/2014	Blog post discussing why the Equal Transit Theory is incorrect.	The author has a bachelors of science in civil and environmental engineering and is a scientific writer. He does not have the most expertise but his reputation as a writer means his blog is still a credible source.

5	http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html 29/12/2014	An article explaining the Bernoulli Effect.	This article is published by Georgia State University, a research university and so is likely to have expertise in the subject.
6	Tritton D.J. Physical Fluid Dynamics, Van Nostrand Reinhold, 1977, Section 22.7 "The Coanda Effect"	A section of a publication explaining and discussing the Coanda effect.	D.J. Tritton has a PhD from Cambridge on "Experiments on Flow past Cylinders and Free Convection". This means he is an expert on the Coanda Effect.
7	www.grc.nasa.gov/www/k-12/airplane/right2.html 18/11/2014	Article explaining how the Coanda Effect generates lift.	Written by a NASA Aeronautics researcher, thus credible due to his expertise.
8	http://virtualskies.arc.nasa.gov/aeronautics/3.html 11/18/14	An article stating the 'Skipping Stone Theory' of lift as correct.	This article is old and the author has no known expertise, despite being by NASA. It appears to be designed for a younger audience and so may not present all the correct information.
9	Appendix 1	Emails between me and a researcher at NASA GRC about why the 'Skipping Stone Theory' of lift is incorrect.	Aeronautics researcher at NASA, has expertise.
10	http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/angatt.html Accessed from Wikipedia 02/10/2014	Article discussing the Coanda effect vs the Bernoulli effect.	This article is published by Georgia State University, a research university and so is likely to have expertise in the subject.
11	Paperaeroplanes.com/blog/ 24/09/2014, 11/09/2014	Various information about paper aeroplanes including lots about aerodynamic features.	I was unable to obtain any information about the author, however, from the language used and the topics discussed it appears he probably has some sort of expertise. This means his credibility is decent but not great.
12	"Blended Winglets." Faye, R.; Laprete, R.; Winter, M. Aero, No. 17., Boeing.	Publication about winglets.	The authors are a Technical Director at Boeing and two Technical Fellows.
13	http://www.racecar-engineering.com/articles/technolo	An article discussing the aerodynamic	Published by Racecar Engineering, a well-known

	gy/can-dimpled-aerodynamic-surfaces-reduce-drag/ 28/12/14	effects of dimples on a golfball.	motorsport publication. This gives them good credibility.
14	www.paperaeroplane.org/Aerodynamics/paero.htm 26/09/2014	An article about paper aeroplane aerodynamics, especially information about Reynolds numbers.	The author is a world record holding paper aeroplane designer. He is also a research based aeronautical engineer. This gives him good credibility due to his expertise.
15	Dave Watt, CFI, Windrushers Gliding Club, 24/07/14	Information on angle of attack, lift and stalling from a talk about spinning.	Dave Watt is the Chief Flying Instructor at a gliding club as well as an a retired airline pilot. This gives him good credibility due to his experience in the subject.

Appendix 1 – Emails between me and Tom Benson at Nasa Glenn Research Centre

Dear Mr Benson,

I've recently been researching paper aeroplane aerodynamics and came upon the theory that air particles deflect off of the bottom of the wing and generate lift. I found your article describing how it is wrong at normal flight speeds (http://www.grc.nasa.gov/WWW/k-12/airplane/wrong2.html). I continued researching lift generation theories and found this article (from a different NASA center) which stated the theory as fact. Could you shed any light on why there is disagreement and why you believe it is wrong?

Many thanks,
Elijah Andrews

Elijah,

The other website is from NASA Ames Research Center in California … I am at the NASA Glenn Research Center in Cleveland. I don't know who the author of the website is … it appears to be well done, but a little light on the science and math. The lift theory being developed at that website is one that is common amongst people who are not aerodynamics experts. They talk about Bernoulli, and they talk about Newton and they want to add the effects of both. I have seen an article in Popular Science where they even assigned percentages … "this wing gets 40% of its lift from the Bernoulli effect (pressure difference) and 60% from Newtonian". This kind of theory is 100% wrong.

Lift actually comes about because in any physics problem one has to conserve mass, momentum (mass x velocity), and energy (mass x velocity squared). " Conserving" means whatever you start out with, you end up with. Conserving means neither creating nor destroying the property (mass, momentum and energy). Newton's three laws of motion for a solid are just statements about the conservation of momentum. For a solid you don't have to worry about the conservation of mass because all of the molecules of a solid stick together. But for a fluid (liquid or gas), it gets very confusing because the molecules are free to move about. If you push on a solid all of the molecules go in the direction you push. If you push on a fluid, some of the molecules that way, but some go perpendicular to the way you push. So for fluids we have to simultaneously (at the same time .. at every instant) conserve mass, momentum and energy. To make things more confusing, momentum is a vector quantity … it has three directions. As I mentioned, Newton's laws of motion are expressions of the conservation of momentum. Bernoulli's equation (relating pressure and the square of the velocity) is derived from the conservation of energy. So in any fluids problem, Newton's laws and Bernoulli's equation have to be satisfied at the same time … they aren't added up or subtracted … they happen at the same time. I have to admit, this is a lot of detailed science … and there is math that describes all of it … and people who are trying to just explain the basics to the general public often don't understand all the details and certainly don't expect a novice to understand them as well. But this idea of conserving mass, momentum and energy is how it works and is what is taught at universities to students of aeronautical engineering. At my website, we get into a lot of these details … I have a webpage with the actual math equations that describe the conservation laws:

http://www.grc.nasa.gov/WWW/K-12/airplane/nseqs.html

They are quite messy! At the Ames website, they talk about computational fluid dynamics

http://virtualskies.arc.nasa.gov/aeronautics/6.html

That is what I do in my “real job” at NASA and it involves solving the equations on my webpage using computers.

Tom

I have a related question to the previous one about the skipping stone theory. A couple of my sources have also mentioned that particles deflecting off control surfaces cause them to be effective. Is this at all true? It follows from your article that if a wing generates lift by turning the air that a control surface does the same.

Thanks,

Elijah

Elijah,

You have it exactly right. If the shape and inclination of the object can turn the flow … lift will be generated. The greater the turning, the greater the lift. And both “sides” of a surface contribute to the lift. Control surfaces cause increased turning when the edges are deflected….. up to the point where they cause the boundary layer to separate and to “stall” the wing.

Tom

Okay, I think I understand why flow turning generates lift, and this excludes the possibility of skipping stone theory because the air doesn't hit the wing in that way because it turns instead, have I got that about right?

Thanks,
Elijah

Pretty good ..

Tom