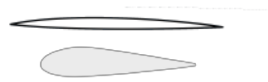
White Paper

Basic Concepts for Aerodynamic Wheels

There are three general approaches to aerodynamics with low velocity airflow applications (1/4 the speed of sound and less).

The following terms will be used to classify these three types of design:

- Thin Airfoil
- Rounded Leading Edge Airfoil
- Boxfish Design



Thin Airfoil designs may look on paper like the simplest and most effective, but it is more commonly used in supersonic shapes where air achieves practical incompressibility. It can be useful to lower speed applications, but the shape does not lend itself to efficient weight to strength for lateral loads, so will tend to be heavier if used in a 3, 4 or 5 spoke design. A similar design is common as a simple profile for alloy blade spokes.

Rounded Leading Edge uses the shape we most commonly associate with an airplane wing. With an airplane wing, the top and bottom camber is different and this produces lift. Wing dynamics need to balance lift against drag as well as many other characteristics such as stall and maneuverability. For bicycle wheels, lift is not desirable, so a neutral, symmetric profile is used. Zero camber. Zero angle of attack. The goal here is Laminar Flow, where air moves smoothly from the point of displacement in front of the leading edge through to replacement aft of the trailing edge.

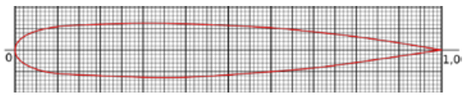


Fig. 1 - Example: NACA 0012B
Commonly referenced profile for laminar flow

Boxfish Design surfaced in the late 1990's through a discovery relating to the contours of the boxfish yielded surprising results. These design elements started showing up in many automobiles, especially economy compacts and minivans. This type of design is often mimicked in styles with only a minimal impact on function and has been showing up as subtle touches in many Triathlon frames and a few deep dish rims, semi-disc wheels and low spoke wheels as of the 2012 product year. Typical styling cues include subtle ridges and swoops as well as sharper angles instead of smooth parabolic curves.

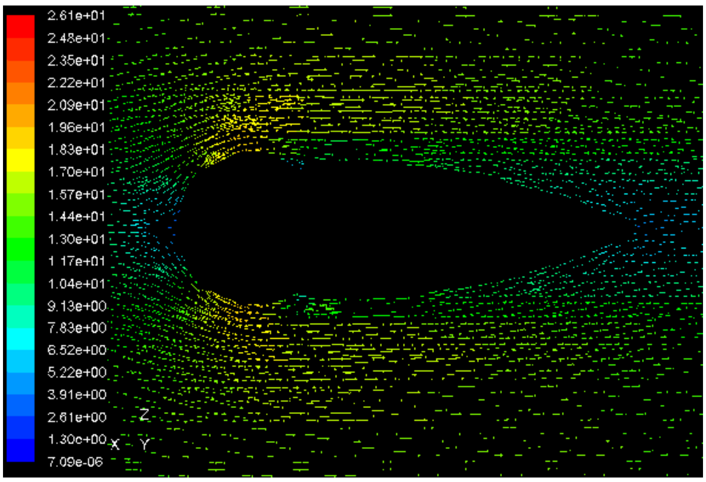


Fig. 2 – CFD model of flow around tire and aerodynamic rim at 50km/h rotation and wind speed

What is the goal?

The purpose of aerodynamics in a bicycle wheel is simply to reduce drag as much as possible. Drag is directly related to turbulence and pressure at the leading edge. If you can reduce pressure and turbulence, you can reduce drag. This must be balanced with a structure that lends itself towards rigidity and strength which are also critical for a successful design. More rigid translates to better performance and handling, while strength allows a lighter build within safety requirements.

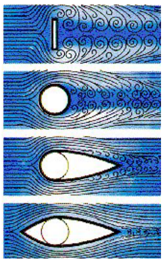
PRO-LITE

White Paper

What is an "Airfoil"?

An airfoil is a shape, usually shown as a cross-section of a structure such as an airplane wing. Any object can be an airfoil, though for aerodynamics, we are mostly considering objects that are shafts, tubes that have aerodynamic function as one of their major goals. For most situations, the airfoil shape remains the same or similar for most of the length of the object. When we talk about the length, for example, of an airplane wing, we will use the term 'planform'.

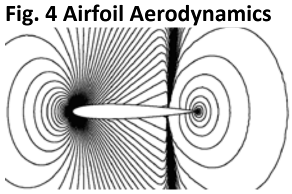
Fig. 3
Airfoils



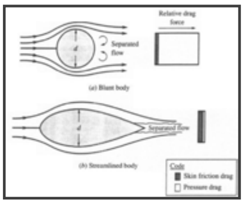
What is the "Leading Edge"?

The key features of the aerodynamic profile include the leading edge and the trailing edge. Pressure is the amount of resistance along the leading edge. Thin Airfoil design uses a sharp leading edge to reduce this pressure which becomes significantly greater at transonic and supersonic speeds where air reaches the limits of its compressibility. For lower speeds, even up to 200mph, pressure at the leading edge is effectively handled by a rounded shape.

Fig. 4 Airfoil Aerodynamics



What is the "Trailing Edge"?



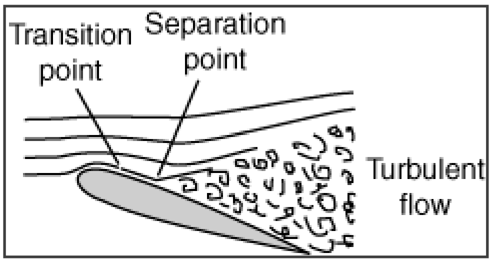
The trailing edge is the edge where air comes back together. Theoretical models often use very sharp points, but carbon doesn't like sharp angles, so in actual product, a slightly rounded trailing edge gives the best results for strength. A cylindrical airfoil has a rounded trailing edge and creates a lot of turbulence.

Fig. 5
Red shows areas of turbulence

What is the "Separation Point"?

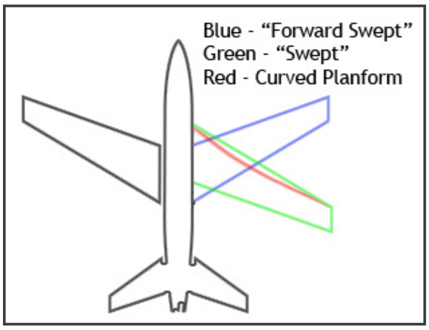
The Separation point is not a part of the airfoil itself. As the speed increases, the pressure in front of the airfoil increases and the pressure behind the airfoil decreases. Where pressure is low, air will be sucked in from surrounding areas to equalize the air pressure. This movement creates turbulence, which in turn creates drag. The point where the air flow around the airfoil is disrupted is called the Separation point. Having a gentle taper from the highest point to the trailing edge will help move this point aft, thus reducing total drag. Surface smoothness is also a factor.

Fig. 6
Relation of the Transition Point and Separation Point to turbulence



What is the "Planform"?

The planform is basically how straight the leading edge of the airfoil is. On a Boeing 747, the wing is basically straight, so we can say that it has a straight planform. On a typical alloy bladed spoke, the planform is also considered to be straight. If an airplane wing points fore or aft, it is called 'sweep'. Because the air rolls onto deeper sections of wing, forward swept designs are very efficient at maximizing air control with a minimum of material used.



White Paper

What is a "Vortex Generator"?

A vortex generator is a surface feature that "trips" the airflow to create controlled vortices. It creates a small zone of turbulence which can reduce the turbulence generated by another feature downstream. On an airplane, these can be seen quite plainly. They are typically used to prepare the air stream in front of an aerodynamic feature (ie the windshield or landing gear) or on the surface of a large irregular body (ie the engines) or to control the separation point, especially where a strong angle of attack is used to generate lift or control (wing/tail surfaces and aileron controls).

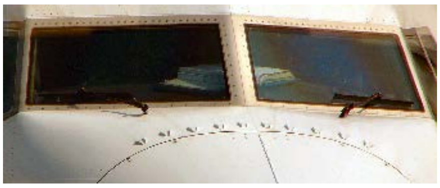


Fig. 7
Vortex Generators to "trip" the air flow and reduce noise over the windshield

Fig. 8 - Vortex generators on the fuselage in front of landing gear and tail/rudder

Vortex generators can take many shapes and include small protrusions, smooth bumps, grooves, dimples and fins. On their own, they increase surface drag, but when combined with another feature, can decrease overall drag.

Vortex generators are typically used to prevent separation. This is primarily critical to prevent wing stall, which causes an aircraft to lose control.

What is the Reynolds Number?

Simply put, the Reynolds number is a value that describes the fluid that the object is passing through, giving a ratio of the speed/the viscosity. There is also a dimension of the object included. For two similar bicycle wheels, this would be the same for both.

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \mathbf{v} L}{\mu} = \frac{\mathbf{v} L}{\nu}$$

As the speed goes up, the Reynolds number goes up. If the fluid gets thicker, the Reynolds number goes down.

For almost any shape, when the Reynolds number is below 2000, the flow is probably laminar. Turbulence starts to show up around Re 2000 and values above Re 10000 are fully turbulent.* These are all characteristics of the fluid, not the shape of the object. The purpose of design is to create shapes and features that will reduce or control turbulence generated by the movement of the object through the air.

What are some Reynolds values for bicycle wheels? (****see below for link to calculator)

It is difficult to answer this due to the variable speed of a rotating wheel, at 20°C, 1 atm, assuming kinematic viscosity of 1.5111E-5, length of 660mm:
@50km/h (8.33m/s) = **Re 607107**, @30km/h (13.9m/s) = **Re 386978**
A baseball (d=75mm) at 100mph = **Re 22186**

> The Reynolds number is a characteristic of the **testing conditions**, *not* a characteristic of the object itself, nor a description of aerodynamic efficiency.

Note that these numbers are provided only to give a rough idea of Re values for bicycle wheels. These values fluctuate for every part of the wheel in motion, so are generally rounded off very liberally (ie to the nearest 100000). In areas of stalled air flow (ie along the leading edge), the Reynolds value can go very low. A larger stall area on the leading edge indicates more pressure drag.

Reynolds numbers are not usually provided for the testing of bicycle wheels since the viscosity of air tends to be fairly constant at the altitudes and weather conditions seen by bicycles. For testing purposes, it is mostly important to standardize the speeds – typically 20 or 30mph or 30, 40 or 50km/h. At these speeds, the Reynolds numbers are close enough that aerodynamic characteristics tend to behave “qualitatively the same”.

Scientific testing generally aims to reduce the number of variable factors, comparing two similar conditions to determine the nature and cause of change. For aerodynamic testing, this means that air density and speed will be kept constant, so changes in shape and texture can be observed. For example, Reynolds values for disc wheels with the same tire and same external diameter will be the same if tested in the same conditions, regardless if one has a textured surface or a boundary layer trip. Non-disc wheels may be slightly more complex and may have the front half of the rim and rear half considered separately, averaged or ignored (treated as a disc) for the purposes of standardization.

An important consideration for Reynolds numbers is that the wheel is “dynamic” (rotating), and wind speeds are often much lower than the speeds of the rider and wheels, so the Reynolds number creating turbulence is local to the area of interaction between the wheel and the air around it. Turbulence in the wind encountered can come from weather-related wind conditions as well as interference from other riders.

What kind of air resistance does a wheel face?
The wheel faces 3 primary directions of resistance.

The simplest of these is direct forward air resistance. This is best addressed by static wind tunnel testing with no rider or the rider not moving. For a wheel, the leading edge is the tire and the rim profile determines the shape of the airfoil. Given that wheels are restricted to being round, the profile as it meets the air is only optimal at the front of the tire. Still, aerodynamic performance does not suffer greatly at other points around the rim.

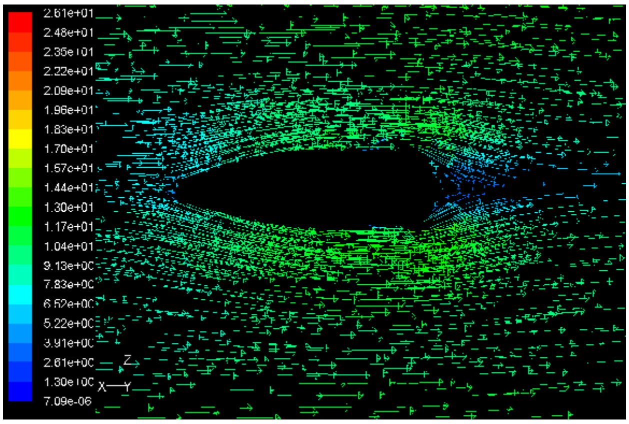


Fig. 9 – CFD model of at 50km/h rotation and wind speed showing small area of trailing edge separation (blue)

A bit more complex is the rotational air resistance. Wheels don’t really spin when the bicycle is in motion like they do if you pick up a wheel and spin it on its axle in your hands. The tire contacts the ground and rolls forward from there. This means that at any given time, the air speed at the point of contact with the ground is zero, gradually increasing to double the speed of the bicycle at the top of the wheel. This means that the spoke design can be directional, with the benefits of the airfoil shape being maximized against rotational resistance where air speed is highest in the top half of the wheel.

The third direction of wind resistance is lateral, such as in crosswinds – referred to as “yaw”. This change in the angle of attack can disrupt the flow around the wheel and can increase (or decrease) drag. Many disc shapes and deep profile rims have been shown to demonstrate “negative drag” in the direction of travel between 10 and 20 degrees of yaw. However, this isn’t a perpetual motion machine, and these effects are counteracted by other forces on wheels – especially on rear wheels. Most companies therefore have chosen to keep designs that work best to reduce forward air resistance and rotational resistance, which are largely predictable and relatively constant under a wide range of conditions.

How much benefit comes from aerodynamics?
It is no secret that the vast majority of air resistance comes from the body of the rider and the vast majority of aerodynamic 'improvements' yield fractions of a percent in total aerodynamic gain, but it's easy to dismiss minor gains as unimportant. The key to understanding these benefits is time.

Where a change of 0.1% in aerodynamics may not sound like much, when considered over the space of one hour, two hours or even 24 hours, the result may be measurable in seconds, even minutes. And that can be significant in any competition. The reality is that most aerodynamic benefits are just a fraction of a percent.

Want to do some more reading?
Some of our source material and additional informational resources:
http://www.efluids.com/efluids/pages/bicycle.htm (compiled by Princeton professors Smits and Royce)
http://www.princeton.edu/~asmits/Bicycle_web/blunt.html (see previous)
http://www.aerospaceweb.org/question/aerodynamics/q0136.shtml
http://iopscience.iop.org/0031-9120/38/6/001/pdf/pe3_6_001.pdf
http://www.daviddarling.info/encyclopedia/D/drag.html
http://en.wikipedia.org/wiki/Airfoil
http://en.wikipedia.org/wiki/Lift_(force)
http://en.wikipedia.org/wiki/Wing-shape_optimization
http://en.wikipedia.org/wiki/Planform
http://en.wikipedia.org/wiki/Camber_(aerodynamics)
http://www.allstar.fiu.edu/aero/wing34.htm
http://user.uni-frankfurt.de/~weltner/
http://www.diam.unige.it/~irro/lecture_e.html (also available in German and Italian)
http://www.grc.nasa.gov/WWW/K-12/airplane/foil3.html

Picture sources:
Fig. 1 - http://www.icmercato.it/naca-0012-airfoil-profile&page=7
Fig. 2 - http://ir.canterbury.ac.nz/bitstream/10092/1800/1/thesis_fulltext.pdf
Fig. 3 - Civil Air Patrol
Fig. 4 - P. Nithiarasu, (2008) "A unified fractional step method for compressible and incompressible flows, heat transfer and incompressible solid mechanics", International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 18 Iss: 2, pp.111 - 130
Fig. 5 - http://commons.wikimedia.org/wiki/File%3AAerofoils_for_different_aeroplanes.svg
By Arnero (Own work) [CC-BY-SA-3.0 (www.creativecommons.org/licenses/by-sa/3.0) or GFDL (www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons
Fig. 6 - http://www.answers.com/library/Aviation+Dictionary-cid-85058
Fig. 7 - http://www.b737.org.uk/fuselage.htm (eyebrowless 737 windshield with vortex generators for noise reduction)
Fig. 8 - http://ir.canterbury.ac.nz/bitstream/10092/1800/1/thesis_fulltext.pdf

White Paper

Also:
http://commons.wikimedia.org/wiki/File%3AExamples_of_Airfoils.svg
By Olivier Cleynen (Own work) [CC0], via Wikimedia Commons

http://commons.wikimedia.org/wiki/File%3AWing_forward_swept.svg
By Steelpillow (Own work) [CC-BY-SA-3.0 (www.creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

http://www.aerospaceweb.org/question/aerodynamics/q0215.shtml

Back to back comparisons between toroidal and flat disc shapes and various similar spoke designs:
http://ir.canterbury.ac.nz/bitstream/10092/1800/1/thesis_fulltext.pdf

Reynolds Numbers References:

$$\mathrm{Re} = \frac{\rho v l}{\mu} = \frac{v l}{\nu}$$

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \mathbf{v} L}{\mu} = \frac{\mathbf{v} L}{\nu}$$

Where:

v = Velocity of the fluid
l = The characteritics length, the chord width of an airfoil
ρ = The density of the fluid
μ = The dynamic viscosity of the fluid
ν = The kinematic viscosity of the fluid

*Reynolds Values:
Sinnott, R. K. Coulson & Richardson's Chemical Engineering, Volume 6: Chemical Engineering Design (4th ed.). Butterworth-Heinemann. p. 73. ISBN 0-7506-6538-6.

**Reynolds Sample Values:
http://udel.edu/~inamdar/EGTE215/Laminar_turbulent.pdf

***Reynolds Calculation Values:
http://www.aerodrag.com/Articles/ReynoldsNumber.htm

****Reynolds Value Calculator: (already calibrated for “normal” air density at sea level)
http://airfoiltools.com/calculator/reynoldsnumber
A baseball (d=75mm) at 100mph = **Re 22186**
Control value checked here: http://www.grc.nasa.gov/WWW/k-12/airplane/balldrag.html
Re (baseball) = 2.2 x 10^5 = **Re 22000**
This is the value of drag coefficient that is used in the HitModeler and the CurveBall Expert simulation programs.