Optimization of Low-Windspeed Bicycle Airfoils

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Abstract

Reducing bicycle drag can dramatically improve rider performance, yet bicycle tube airfoil designs are still hand-tuned, and automatic optimization has remained largely unexplored. In this work, we first perform an extensive comparison of industry-standard low-windspeed airfoil parameterization methods, including NACA and PARSEC, and demonstrate that current methods perform poorly as bicycle tube airfoils because they fail to account for high yaw values or optimize lift over drag. We observe that truncation alleviates this issue, and show that a mixed parameterization model helps improve robustness to initialization differences. Finally, we propose a simple linear interpolation method that consistently outperforms standard parameterization methods across a range of yaw values with minimal hand-tuning.

1 Introduction

In competitive road cycling, over 90% of a cyclist's power goes towards fighting air resistance, and 25% of this drag is attributed to the bicycle. It's not uncommon for professional cycling races to be won by thousandths of a second, so even marginal improvements in bicycle aerodynamics can determine the racers who stand on the podium on events such as Le Tour de France or the Olympics. Currently, most bike manufacturers use computational fluid dynamics (CFD) simulations to evaluate prototypes, and make manual changes to design parameters, resulting in extended periods in between tests, and exploration of only a small portion of the design space. Furthermore, though the literature on general airfoils is expansive [15], low-windspeed airfoil optimization has historically inhabited a small niche in aerodynamic science, and many assumptions made for high-windspeed airfoils may not apply [2].

The profiles of most airfoils in the literature are described by a vector of 50-80 coordinate pairs located on the profile surface, usually given by NACA parameterization [6]. However, CFD evaluations are computationally expensive, and it is therefore advantageous to search for an effective parameterization that requires fewer evaluations to optimize. Airfoil shape parameterizations must consider three main objectives: represent a wide range of existing airfoils, formulate and impose the parameters in a simple way, and allow for efficient and effective optimization [4].

Optimizing bicycle airfoils brings several unique challenges. There is no gradient information for the objective function, which is an expensive CFD simulation. It is also a multi-objective optimization problem because we have to consider a range of yaws from cross-winds. Though cross-wind effects are usually negligible in high-windspeed problems, bicycles see much higher yaw angles because they travel at speeds similar to common wind speeds. Finally, predicting fluid dynamic behavior at low-Reynolds numbers with significant turbulence is notoriously challenging [14].

Here, we optimize cross-sectional tube shape for bicycles. We first apply NACA and PARSEC shape parameterizations and show that performance is poor for high yaw values, and introducing a truncation parameter rescues this performance. We then introduce two simple parameterization methods that boosts performance across yaw values while improving robustness to initialization differences: a mixture model of standard parameterizations, and an interpolation model.

2 Related Work

2.1 Low-windspeed airfoil optimization

There is a large body of existing research in optimization of low Reynolds Number airfoils. Though there are significantly fewer studies specific to bicycle frame tubes, we hope to adapt some methodology from work in similar spaces. Jaroslav Hájek's thesis "Aerodynamic optimization of airfoils and wings using fast solvers" shows the use of an evolutionary algorithm paired with fast solvers for fluid dynamics approximation to optimize wing shapes, though at higher Reynolds numbers [8]. "Robust aerodynamic shape optimization—from a circle to an airfoil" from He et al. is another example of automated optimization, but using a sparse nonlinear optimizer and quasi-Newton methods [10].

The current state-of-the-art bicycle tube airfoil is the Kammtail Virtual Foil

(KVF) by Trek, which was developed by hand-tuning airfoil shape parameters before CFD evaluation [9]. This design was validated using wind tunnel testing, prototyping, and rider testing, resulting in the "Trek Team Speed Concept" bike.

3 Methodology

3.1 CFD simulations

In order to evaluate the aerodynamic properties of each design, we used XFOIL, a popular subsonic airfoil development software [5]. In order to optimize our designs, we used Python optimization scripts, so in order to interface with XFOIL, we started a subprocess for each new design and piped commands as well as the design into XFOIL, and read results from a logfile. This allowed us to automate the optimization process with Nelder-Mead optimization.

As always with CFD simulations, there are many modelling decisions, and one must take care to choose parameters carefully. When calculating drag, we chose a tangent wind speed of 24 mph, a tube size of 2.25 inches, and an air temperature of 70°F, resulting in a Reynolds number of roughly 38,000 and a Mach number of 0.03. We tested all airfoils at 0°, 1°, 2°,..., 10° yaw angles. We weighted the drag coefficients at each angle according approximately to wind distribution in race conditions. Many different groups have measured wind yaw at race speeds to be roughly normally distributed $\sim \mathcal{N}(0, \sigma^2)$ with σ^2 around 6° to 9°, depending on location and weather [1]. In addition, the Union Cycliste Internationale (UCI) regulations state that bike tubes must have cross-sectional area within a 3-to-1 ratio. Since tubes with a greater depth/width ratio are known to have comparatively less drag, we constrain our designs to follow this 3-to-1 ratio. [1]

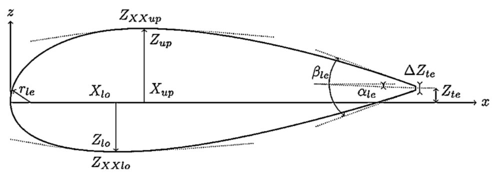
3.2 Optimization

We used the Nedler Mead Optimizer [16] from the SciPy optimization library [7]. We convert the multi-objective optimization problem over a range of yaws by a weighted summation proportional to the expected frequency of encountering each wind yaw, and leave the analysis of the Pareto front as future work.

3.3 NACA and PARSEC Shape Parameterization

The NACA airfoil standard were developed by the National Advisory Committee for Aeronautics (NACA) in the late 1920s, and can be described using a code

[1] https://github.com/elipugh/aa222_project



PARSEC parameter	Geometry parameter	Definition
p_1	r_{le}	leading edge radius
p_2	X_{up}	upper crest position in horizontal coordinates
p_3	Z_{up}	upper crest position in vertical coordinates
p_4	$Z_{XX_{up}}$	upper crest curvature
p_5	X_{lo}	lower crest position in horizontal coordinates
p_6	Z_{lo}	lower crest position in vertical coordinates
p_7	$Z_{XX_{lo}}$	lower crest curvature
p_8	Z_{te}	trailing edge offset in vertical sense
p_9	ΔZ_{te}	trailing edge thickness
p_{10}	α_{te}	trailing edge direction
p_{11}	β_{te}	trailing edge wedge angle

Figure 1: Parsec variable definition.

of 4 numbers specifying camber lines, maximum thickness, and nose features [6]. The first digit describes the maximum camber as percentage of the chord. The second digit describes the distance of maximum camber from the airfoil leading edge in tenths of the chord. The last two digits describe maximum thickness of the airfoil as a percent of the chord [15]. The formula for the shape of a NACA foil is expressed below:

$$y_t = 5t[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4]$$

where x is the position along the chord from 0 to 100%, y_t is the half thickness at any given value of x, and t is the maximum thickness as a fraction of the chord.

The PARSEC parameterization defines a set of shape functions, and was popularized by Sobieczky [13]. There have been several adaptations to PARSEC, including Bezier curve parameterizations [4] and optimizing PARSEC using genetic algorithms [3]. Here, we study the standard PARSEC formulation, as shown in Figure 1.

4 Experiments

4.1 Standard parameterization methods perform poorly

We first optimized our airfoil using standard NACA and PARSEC parameterizations. While these are very popular and effective airfoil parameterizations for wings or turbine blades, they perform poorly as shapes for bike tubes. After optimization, NACA and PARSEC achieved weighted drag coefficients of 8.67 and 5.41, respectively. The drag curves for NACA and PARSEC are shown in blue and green respectively in 3. The optimal designs with weighted drag coefficients are shown in Figure 2. While PARSEC performs better at lower yaws, both designs have especially high drag for yaw values higher than ±7.5 degrees.

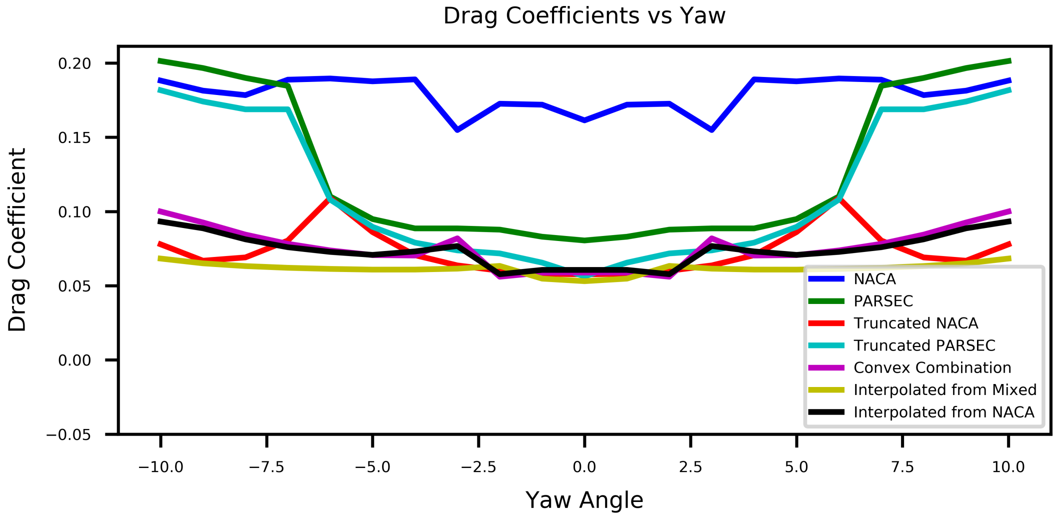


Figure 2: Comparison of airfoil drag over a range of yaw values. NACA without truncation (blue), PARSEC without truncation (green), NACA with truncation (red), PARSEC with truncation (teal), convex combination of NACA and PARSEC (purple), and linear interpolated (tan).

4.2 Truncation and mixing provide robustness over yaws and initialization values

Previous works show that truncating the end of the bicycle tube airfoil improves performance over a wider range of yaw angles. Here, we automatically tune this feature by incorporating an additional truncation value to both standard parameterization methods. Adding this truncation parameter dramatically improves performance, especially across higher yaws (Figure 2). For NACA and PARSEC, the optimal truncation parameters are learned to be around 0.4 and 0.8 respectively.

In practice, the NACA models were highly sensitive to parameter initialization, and required extensive hand-tuning to converge. To address this we sought to combine the robustness of the PARSEC model and the performance of the NACA model by designing an airfoil with both truncated NACA and PARSEC parameters, and take a learned convex combination of both designs. This method improves empirical robustness to initialization, and matches our best performance from any of our previous methods over different yaws (Figure 2, purple). Qualitatively, these results closely match hand-crafted state-of-the-art designs (Figure 3, bottom).

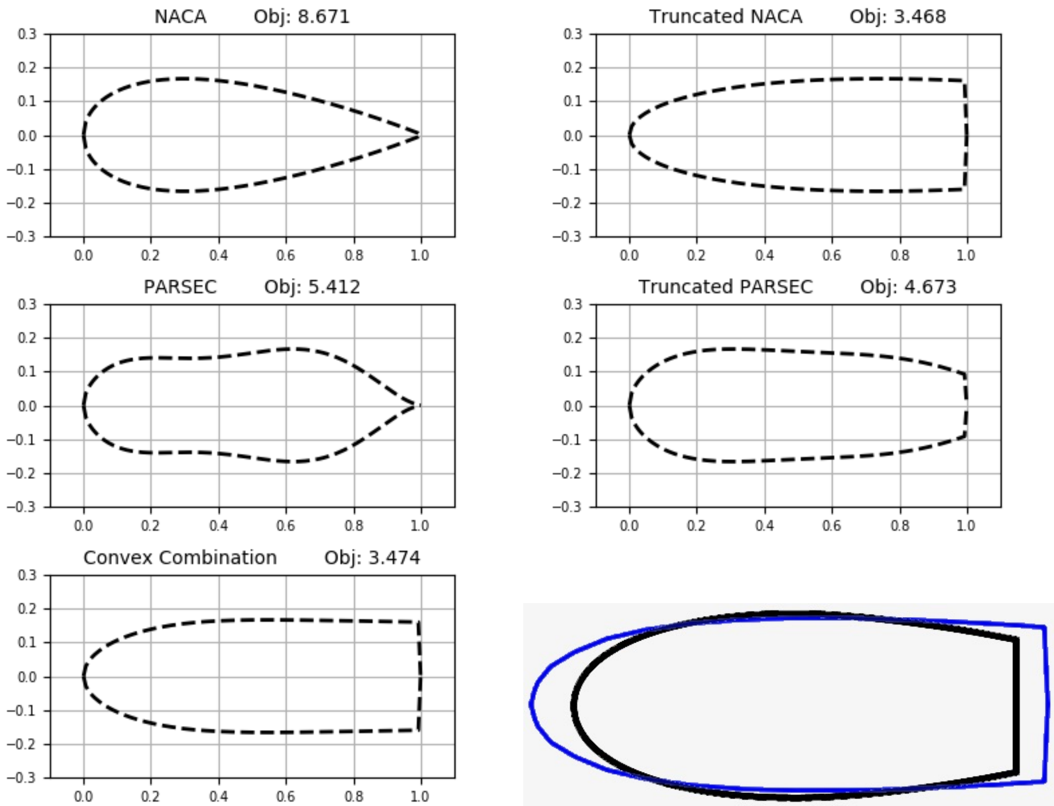


Figure 3: Airfoil designs. NACA without truncation, (top left), NACA with truncation (top right), PARSEC without truncation (middle left), PARSEC with truncation (middle right), learned convex combination (bottom left). The convex combination design superimposed on Trek's KVF airfoil, with our design in blue and KVF in black (bottom right).

4.3 A simple interpolation method improves performance

Though the NACA shape parameterization method has withstood the test of time for a range of airfoil optimization tasks, the truncation results above suggest that additional degrees of freedom beyond standard NACA or PARSEC parameterizations may improve airfoil performance for our specific task. Here, we demonstrate that a simple linear interpolation method can further reduce drag.

In order to give the airfoil more degrees of freedom, we parameterized an airfoil by simply listing out points on its surface, and then linearly interpolating. Firstly, it was apparent that constant spacing of these points along the x-axis created a jagged airfoil, unless there was very high dimension. To remedy this, we used half-cosine spacing of the points along the front edge, and then evenly spaced the points on the back half of the airfoil. Half-cosine spacing, proposed by Lan et al.

is achieved by transforming evenly spaced ticks with $t'_i = \frac{1}{2} - \cos(t_i)$ [12] [11]. In our experiments we interpolated with 16 points.

A second trick was to notice that with a reasonably nice initialization, for example another optimized foil, any change to a single coordinate makes the drag worse, since this change creates either an indentation or a spike in the profile. To remedy this, we parameterized the difference from each point to the next, so that from a design y with points y_i at ticks t'_i, we instead parameterize $y'_i = y_i - y_{i-1}$, then reconstruct y when evaluating drag.

In order to facilitate more stable optimization, we initialized our interpolation model using our best-performing airfoil designs: NACA and the mixed model. The resulting airfoils and weighted drag coefficient scores are seen in Figure 4. When initialized with the mixed method, interpolation gives a 20% boost on top of the best-performing parameterization models, improving on almost all yaw values Figure 2 (tan).

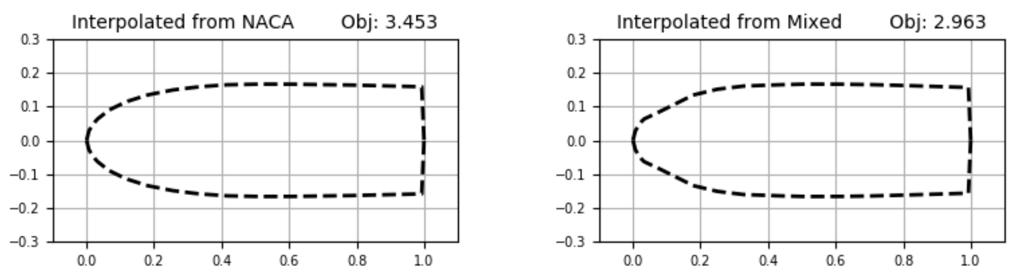


Figure 4: Interpolation designs, from NACA (left) and from the mixed model (right).

5 Conclusion

Overall, we show that it is not only possible to optimize for parameter values, but to also *automatically discover* the proper shape parameterization. We show that a few key insights are important for bicycle tube airfoil optimization: (1) standard shape parameterizations have high drag at high yaw values which can be rescued by truncation, and (2) parameter initialization affects design convergence. When provided a good initialization, our interpolation model can optimize in a stable way and benefit from the additional degrees of freedom to make local design changes to perform well across the entire range of yaws.

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