

High-Downforce Airfoil Design for Motorsports

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ABSTRACT

Using a combination of inverse airfoil design techniques, rapid interactive analysis methods, detailed computational fluid dynamics (CFD) and wind tunnel testing, aft loading of an airfoil has been explored as a design direction for high-downforce airfoils for race car rear wing applications while ensuring performance sustainability across a wide angle-of-attack operating range. Unlike in aircraft oriented high-lift airfoil designs, pitching moment constraints can be circumvented for race vehicle wing designs and this allows for further design freedom in the quest for downforce. The PROFOIL inverse design code was used to design a candidate airfoil exhibiting downforce maximized using aft loading at low Reynolds numbers. The resulting airfoil has a maximum lift coefficient of 2.5 at a designed Reynolds number of 300,000 and shows that aft loading on an airfoil is conducive to high-downforce requirements and is a favorable design direction when considering airfoils for race car wing applications. Comparisons have been made with airfoils representative of the high-lift design philosophies of Liebeck, Wortmann and Selig.

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INTRODUCTION

Downforce in motorsports has been one of the key parameters determining race vehicle performance envelopes for over four decades now. Along with power, weight, and tires, it is one among the four most important parameters for which open wheel race cars such as Formula 1 cars are optimized [1]. Since the ground effect era of the seventies, Formula 1 and other open-wheel race car designs have been dictated by the preferred aerodynamic layout and are designed to work best with the wings and other elements of the aerodynamic package [2]. The use of the Ford Cosworth DFV eight cylinder engines by some teams in the seventies as opposed to the considerably more powerful twelve cylinder, horizontally opposed engines (notably, Ferrari) is a case in point. The massive aerodynamic downforce benefits available from ground effect as a result of the inverted airfoil shape of the vehicle underbody were being explored by the aerodynamicists. Ultimately, even with a less powerful engine, the aerodynamic downforce resulted in a car that was superior in vehicle dynamics and track performance [1].

While the different components of an aerodynamic package contribute varyingly to the downforce levels and resulting flow fields, only the front and rear airfoils and wings lend themselves to theoretical aerodynamic analysis methods and techniques for design. Other components and body shape designs still rely on experimental and numerical

data at the design stage [1]. But as has been highlighted by Agathangelou and Gascoyne [4], the front wing flow is complicated by ground effect (as a result of the close proximity to the ground) and the close presence of the front wheels. The rear wing, though, sees relatively 'clean' flow as it is mounted higher than the bodywork elements in order to gain access to free stream velocities [4]. Design of the rear wing and airfoils can be explored using existing aerodynamic theories.

The focus of this paper is to present aft loading as a design direction for the design of airfoils intended for use on rear wings or wings with reduced influence due to external flow field structures. A candidate high-downforce airfoil has been designed to highlight the design methodology and underscore the downforce gain obtainable for such a design direction.

The first section explains the design direction provided by the aft loading and compares the prominent high-lift airfoil design philosophies and their respective merits and demerits when it comes to motorsports applications. The second section deals with the implementation of the aft loading design philosophy applicable to high-downforce requirements relevant to motorsports and the design and analysis methods used in this effort. Examples are included to illustrate the use of the multi-point inverse design method (PROFOIL) [15], to generate candidate airfoil shapes which were then analyzed using the XFOIL (single element) [5] and MSES (multi

element) [6] codes to provide viscous predictions quickly and efficiently and thus serve as feedback to the designer to further refine the performance of the airfoil under consideration. These codes allowed for rapid analysis of the airfoils at several angles of attack, Reynolds numbers, and for several flap configurations.

The next section deals with the results are from wind tunnel testing and CFD simulations, which were used to corroborate the results of the optimized airfoil shape. Surface pressure distribution, force and moment data, and oil-flow visualization photographs from wind tunnel tests conducted in the NCSU subsonic wind tunnel provide comparisons with XFOIL/MSES and the CFD predictions.

This study will be presented using a high-lift single element airfoil configuration developed for effectiveness even at low speeds. The design and testing was therefore performed at low Reynolds numbers ranging from 300,000 to 600,000 to provide a realistic estimate of the feasible aerodynamic gains even at these cornering speeds. Computational results at higher Reynolds numbers are also considered to establish the validity of the design direction with respect to its applicability to higher rungs of open wheel racing and the consequent higher speeds.

HIGH DOWNFORCE DESIGN PHILOSOPHY

For a motorsports airfoil, the primary requirement is a high maximum lift coefficient [7]. After this requirement is satisfied, various other criteria can be considered in the design to ensure proper functioning of the high lift system under various operating conditions. We will consider some of these scenarios and examine some of the existing low Reynolds Number (LRN) high lift airfoil designs that have been developed before for various aeronautical applications such as low speed aircraft [8]. The distinct design philosophies in this regime include the approaches taken by Liebeck [7], Eppler [11], Wortmann [10] and Selig [8]. To study the applicability of aft loading to motorsport applications, it is necessary to understand the interdependence of various airfoil characteristics upon one another. It is well known[8] that as pitching moment increases, maximum lift coefficient increases along with the pressure recovery becoming convex, as is represented in [Figure 1](#). Other observable trends from the same figure indicate that as an airfoil tends towards a more concave loading, high lift is achievable along with an increase in the rapidity with which stall is reached('fast stall' [8]).

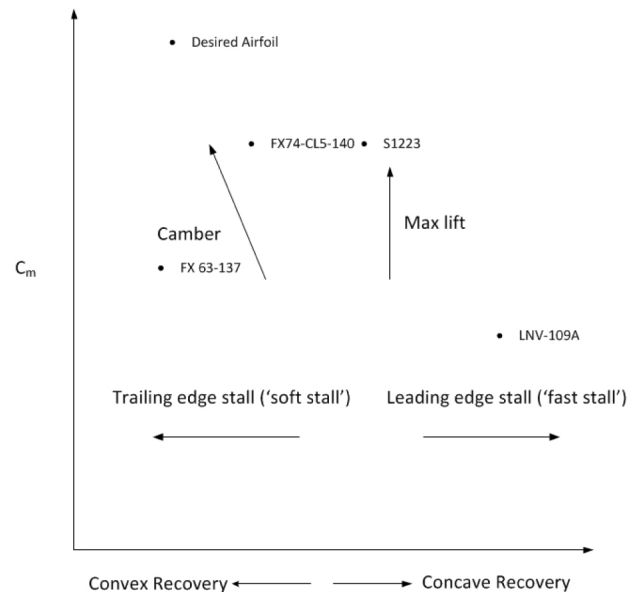


Figure 1. Low Reynolds number airfoil characteristics as a function of pitching moment and stall type.

From a historical perspective, two distinct methodologies were developed in the quest for high lift. Several Liebeck airfoils are good examples of the first type where a large rooftop suction level is employed followed by a Stratford pressure recovery (or concave pressure recovery) [12]. This leads to hard stall characteristics and high lift with low pitching moment. The second approach is that used by the some of the Wortmann airfoils where the reliance on a suction peak is reduced and more emphasis is placed on aft loading (convex pressure recovery) in order to provide softer stall characteristics [10]. A third 'middle ground' methodology is reflected by the Selig and Eppler high lift airfoils where a combination of the aforementioned design philosophies are utilized in combination to provide high lift at LRN[8].

The Liebeck airfoils rely on a Stratford boundary-layer inverse solution whereby a pressure recovery distribution can be found that continuously avoids separation of the turbulent boundary layer. It is meant to recover the maximum possible pressure rise in the shortest possible distance. A high rooftop C_p value can be specified with the desired roof top length, which can then be recovered using an inverse solution that gives the Stratford distribution for that particular case of rooftop dimensions [7]. This is an approach that has worked well for the applications it has been designed for and provides a high lift value with low pitching moment coefficients. An example of this type of pressure recovery is shown in [Figure 2a](#) using a Liebeck LNV-109 airfoil. The Stratford recovery also represents the optimum distribution for low profile drag [11] and this leads to some of the highest lift to drag ratios for these classes of airfoils [12]. But this makes the boundary layer on the upper surface very sensitive to surface imperfections that may trip the flow.

studied the effect of premature flow transition on airfoils designed with upper surface pressure distributions having laminar rooftops and Stratford-type recovery. They demonstrate the drastic performance drop due to the effects of rain drops close to the leading edge. Motorsport applications often have wings positioned close to the ground, and this makes their surfaces susceptible to various bits of track and tire debris. These particles can potentially act as trips and, on airfoils with a Stratford-type pressure recovery, can cause loss of lift. Depending on the Reynolds number, the trips may sometimes act beneficially and prevent the separation bubbles. But this induces an inherent uncertainty when the aerodynamics data is to be used in performance prediction suites such as lap simulations and other vehicle dynamics simulations which rely on aerodynamic performance data for a wide range of simulated operating conditions. Figure 3 shows an XFOIL prediction of how a high lift Liebeck LNV-109 airfoil [20] reacts to the flow tripped at $\frac{x}{c} = 0.1$ with a large drop in C_{lmax} . High performance airfoils reliant on carefully controlled adverse pressure gradients thus show a rapid deterioration in performance outside a narrow envelope [12].

Stratford recovery also results in the airfoil exhibiting hard-stall which is characterized by the coefficient of lift decreasing rapidly with increasing angle of attack beyond stall. Eppler [11] argued that the sensitivity of the turbulent boundary layer in a Stratford distribution, which is on the verge of separation by design, can be a cause of hard stall as the unsteadily moving transition point can change the initial conditions of the pressure recovery such that the turbulent separation is also unsteady. A race car often sees a large variation in speed across a race track which can change the operating Reynolds number from 200,000 to 600,000 (for Formula SAE).

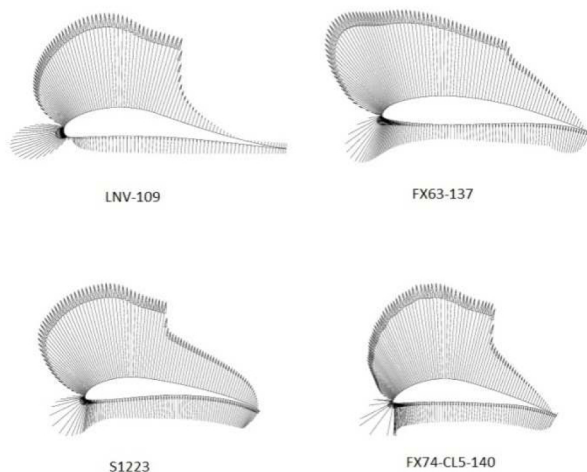


Figure 2. Pressure vectors computed from XFOIL for an angle of attack of 5° to show airfoil loading.

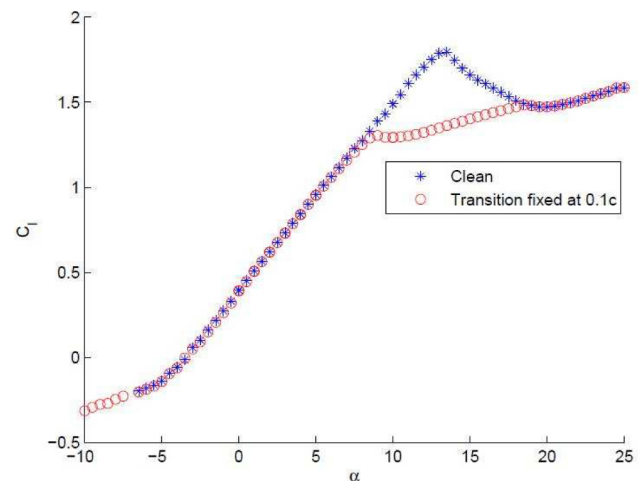


Figure 3. XFOIL prediction for Liebeck LNV109a airfoil performance at $Re=300,000$ with free transition and transition fixed at $\frac{x}{c} = 0.1$.

The range could be larger in either direction depending on the motorsports series in consideration). So these variations can cause an increase in adverse pressure gradient which then causes a fast moving turbulent separation point. Eppler suggested that concave pressure recoveries should be used but they should not be as steep as the Stratford distribution at the beginning. This forms the basis for Eppler's and Selig's high lift airfoil designs [11] where a moderated degree of concavity is allowed into the pressure recovery along with aft loading.

Even though a motorsports wing does not see large changes in angle of attack during forward motion, it is necessary to have as wide an operating range as possible in order to give the aerodynamicist and the vehicle dynamicist enough options when it comes to car setup. The rear wing is often used to balance the car (after the front wing setup has been completed) to compensate for possible undesired characteristics of the car endowed to it by pre-existing handling traits [4]. In the work done by McKay and Gopalathnam [13], an airfoil's effect on overall lap times was computed for the entire range of its lift curve while accounting for wing aerodynamic considerations. The airfoils under consideration in that study exhibited a hard stall characteristic and based on the results of their study, it is evident that lap times deteriorated post stall. Despite profile drag being large in the post-stall regimes, a soft stall can extend the range of available performance at C_{lmax} . So one of the requirements is that a high downforce airfoil should possess a soft stall and should sustain high C_l for a large angle-of-attack range near stall to provide flexibility during car set up.

Due to the very low aspect ratio high downforce systems that race cars employ, the primary source of drag comes from the induced component of overall drag. Profile drag values are thus much lower than the resulting overall drag values.

This allows the design to focus on downforce as opposed to airfoil L/D. Therefore the chief concern in motorsports airfoil design is not one of profile drag reduction [7, 13]. Instead it is a maximization of downforce and the ability of the designed airfoil to sustain the highest possible levels of downforce across a wide range of physical and aerodynamic adversities. Hence a highly concave pressure recovery employing a Stratford distribution is not the ideal solution for a motorsports airfoil design. Rather the goal is to maximize downforce and retain high levels of performance across a broad range of operating conditions.

Wortmann's approach with the FX-63-137 consisted of aft loading with more gradual initial gradients. The design approach with this airfoil was to increase $C_{l\max}$ primarily by adding pitching moment [8]. Wortmann argued that in the case of a concave pressure distribution, initial thickness effects on the turbulent boundary layer are much stronger than for pressure rises with smaller initial gradients [10]. This gives the FX63-137 a convex pressure distribution, as seen in Figure 2b, along with an increase in length of the representative pressure vectors on the lower surface at the aft portion of the airfoil, thus indicating aft loading. Eppler showed that the lift of an airfoil with concave recovery could be improved using aft loading and this was meant to espouse both concave pressure recovery and aft loading as a means to enhance high lift performance. An example of this design direction is the Wortmann FX74- CL5-140[Figure 2d], which is a high lift design that was tailored for high lift performance at a higher Reynolds number than those considered here. It uses a more gradual initial pressure recovery compared to Stratford recovery airfoils along with aft loading, as shown in Figure 2d. Selig adapted concave recovery and aft loading to produce airfoils optimized for high lift at LRN. The S1223, shown in Figure 2c, produces the maximum lift currently for airfoils operating in this regime.

The Eppler, Wortmann and Selig approaches have so far been effective in generating airfoils with high $C_{l\max}$ values for this regime. But due to their constraints born out of adhering to aeronautical considerations, it is felt that an approach more tailored to high downforce generation for motorsports can yield higher $C_{l\max}$ values and satisfy requirements such as performance sustainability across a large range of angles-of-attack, soft stall characteristics and a relative insensitivity to adverse surface roughness effects on the performance characteristics of the airfoil. This approach eliminates any pitching moment constraints imposed in previous designs and attempts to use aft loading as the chief driver towards maximizing downforce while maintaining a rudimentary level of concave pressure recovery that has been kept gradual to ensure airfoil stability under varying operational conditions.

DESIGN IMPLEMENTATION

The design implementation was done using the PROFOIL multi point inverse airfoil design code [14, 15]. PROFOIL

was for used rapid interactive design by specifying the inviscid velocity distributions and analyzing the resulting candidate airfoils in codes with viscous analysis capabilities such as XFOIL and MSES [6, 5]. PROFOIL was used with a MATLAB-based graphical user interface (GUI) [16] which helped execute the various elements of the design code interactively and concurrently plot the resulting airfoil with its constraints and the specified velocity distributions. Many features of PROFOIL are well suited to designing for motorsports and maximum downforce. For instance, it permits control over the design of the transition ramp and this can be used to influence the characteristics of the laminar separation bubble. The turbulent boundary layer development can also be prescribed to avoid separation by a certain design margin [15].

The PROFOIL code consists of an inverse design methodology with an integral boundary-layer method for rapid analysis at the design points. It allows the designer to divide both surfaces of the airfoil chord into segments along each of which the velocity distributions can be prescribed as functions [14]. A design angle of attack, α^* , is specified for each of these segments to tailor the velocity distributions. For a segment, α^* is the angle of attack relative to the zero lift, α_z at which the segment has zero velocity gradient. So if the α_z of the airfoil is greater than the α^* for a particular segment on the upper surface, then that particular segment will experience an adverse pressure and vice versa. So increasing or decreasing α^* can change which parts of the airfoil experience adverse gradients at various angles of attack.

The design process consisted of various candidate designs being produced and compared against a backdrop of the required parameters. Every instance where the candidate airfoil failed to meet the specified design goals, the experience gleaned from that particular iteration was useful in redesigning the airfoil to facilitate a convergence onto the desired performance specifications. This iterative process continued until a successful airfoil meeting the pre-set performance goals was generated. Despite the computational advances in optimization and inverse design, it is still not possible to fully automate the airfoil design procedure and it still remains a sophisticated cut-and-try procedure that is reliant on the designer's judgment to provide the right direction [17].

The α^* values were individually manipulated and kept high over the upper surface to reduce the severity of the recovery gradient adversity in order to provide soft stall and ensure that $C_{l\max}$, or values close to it, were available over a large angle of attack range. The leading edge α^* values were set higher than 30° to ensure that even at high angles of attack, the velocity gradient isn't very adverse, so as to reduce the reliance on suction peak related performance and the associated fast movement of the turbulent separation point at high angles of attack. Along with these α^* manipulations, several constraints were used to achieve the desired airfoil characteristics. A thickness constraint was used to change