Proceedings of CONF-MPCS 2026 Symposium: Theoretic Physics and Plasma Physics
DOI: 10.54254/2753-8818/2026.DL33504

A Review of Aerodynamics, Optimization and Track-Related Performance of Formula One Front Wings

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Abstract. Formula One (F1) is becoming more and more popular and competitive in recent years. As a significant component of F1 racing car, front wing has a huge impact on downforce, drag, wake management and performance of the car. Therefore, the study on the front wing should be given the highest priority. This paper provides a review of the aerodynamic performance, airfoil optimization and performance of F1 front wings on the tracks. It systematically summarizes the parametric and adjoint-based aerofoil optimization focusing on the front wing, brake ducts and wheels. The fluid-structure interaction (FSI) is also included, which focuses on the of aeroelastic deformation causing by high-speed oncoming airflow. Besides, aerodynamics behaviors in real racing scenarios are critical to analyse, including the wheel-to-wheel competition, damage of endplates, leading to different aerodynamic performance on straights and corners with various speed. The comparison of different types of large eddy simulation (LES) and behaviors of distinct methods of RANS are also included. Finally, existing limitations are pointed out and future directions are given to provide references for the design and optimization of racing cars under real competitive conditions.

Keywords: F1, front wing, CFD, optimization, FSI

1. Introduction

Formula One is one of the most technologically advanced motorsports, where aerodynamics efficiency almost dominates the velocity on straights and various-speed corners, reflecting as a few tenth of second faster than opponents on the track and more points on the ranking list which are related to the bonus. As a component interacting with high-speed oncoming airflow, the front wing plays an irreplaceable role of the car, since it not only causes almost 30% downforce of the F1 car, but also influences the behaviour of following components such as suspension, wheel, floor and so forth [1]. Meanwhile, the shape, dimension and the number of elements is strictly limited by FIA (Fédération Internationale de l'Automobile) and may be changed due to the variation of the regulations.

In recent years, a number of researches have explored front wings behaviour by utilizing the technologies of computational fluid dynamics (CFD), distinct algorithms of optimization, fluid-structure interaction (FSI) and so on. Based on skills and tools mentioned before, studies focusing on multi-elements front wing with other components (brake duct, wheel,suspension etc.)

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DOI: 10.54254/2753-8818/2026.DL33504

optimization, aeroelastic deformation and several scenarios only happened on race track have conducted. However, most studies concentrate on interaction of limited components in ideal conditions, causing a insufficient concerns of accidents occur in reality and influence of the entire racing car.

Therefore, this paper aims to offer an integrated review of recent progress in aerodynamic designs, optimization of wings with surrounding components, aeroelasticity, performance of F1 front wings in real tracks and comparison of few simulation methods. Finally, existing researches limitations are identified, and potential ways for the future are proposed related coupled simulation with optimization under competitive racing scenarios.

2. Aerodynamic design optimization of F1 front wings

2.1. Parametric and adjoint-based optimization

A study establishes a parametric and adjoint-based optimization framework of five-element F1 front wings based on the 2021 FIA regulation with proper simplification. In parametric optimization, Gaussian Process (GP) is used as the Response Surface Model (RSM) to interpolate data and establish the response surface based on the NACA profile and FIA rules. After that, to find the best profile, NSGA-II optimization algorithm is employed to maximize life coefficient (C_L) and minimize drag coefficient (C_D). In adjoint optimization, the RBFmorph and-on in ANSYS platform is used to deform the computational mesh based on the optimization result in first process. 20 times are set as the iterations of this model to compute the local sensitivity without improving performance due to excessive shape changing and airfoil not allowed by FIA regulations. Compare to parametric optimization, in this stage, lift-drag ratio ($\frac{C_L}{C_D}$) is concerned instead of only the maximization of C_L or C_D[2, 3]. The entire optimization framework is shown in Figure 1.

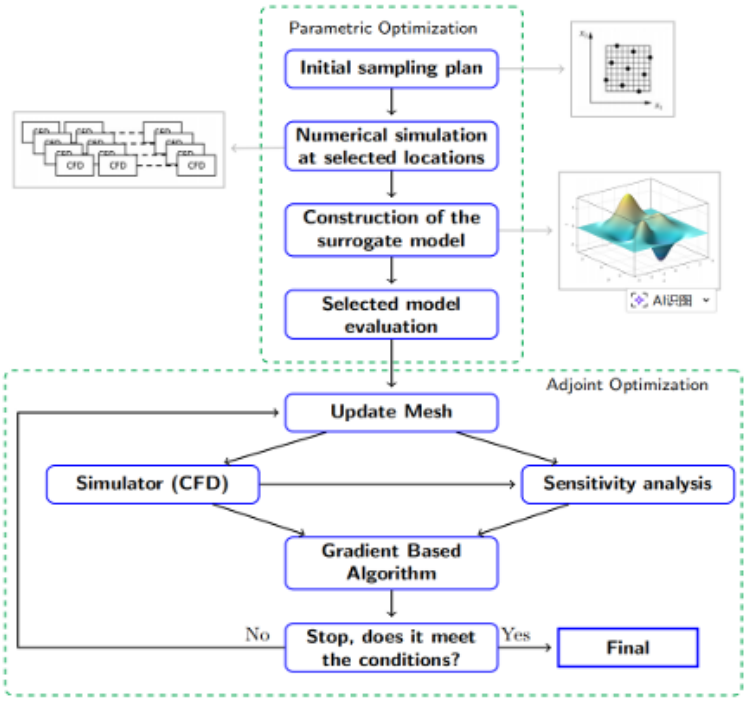

Figure 1. Optimization framework [3]

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2.2. Model and CFD setting

Due to limited computational resource, both studies focus on 2D sections instead of 3D surface model, and few sections along the profile are established for following studies. The 3D wings are established by employing NURBS surface fitting. It is worth to note that second study also create few cross-sections along the car body, specifically behind and in front of the wheel and brake duct since objects behind front wing are also considered [2]. Both researches use SST k - ω to close the result of Reynolds - Averaged Navier Stokes simulation (RANS) turbulent simulation, because Large Eddy or Direct Numerical Simulations have more computational cost [2]. Hexahedral meshes are employed in these researches due to the convention, and mosaic form of cell (tetrahedral combine with hexahedral) do not show better performance. One research uses 30 kph as the inlet velocity, while another uses 50kph, both reflecting proper availability [2,3].

2.3. Result of optimization

The team finds that the five-element front wing by using adjoint optimization gains 25% performance increase with lower drag and higher downforce than the result of parametric method, showing the superiority and reliability of adjoint method [3]. The team also conduct the optimization with brake ducts and wheels, receiving similar outcomes. Result of parametric method has more consistent loads distribution with moderate higher downforce-drag ratio. However, adjoint method sacrifices slight amount of drag to enhance downforce [2,3]. Besides, near the endplate, vortex of adjoint design marginally detaches from the body, which may conduce lower drag than parametric design [2].

3. Fluid-Structure Interaction and aerodynamic performance of F1 front wing

3.1. Numerical and turbulence model

This research uses two-way coupling Fluid-Structure Interaction (FSI) by connecting the high performance computing system (HPC) with complex solving process. After the analysis on two driving height with low Mach condition, the team use Spalart-Allmaras model as the solution of RANS equation [4].

3.2. Aeroelastic deformation and structural response

Through FSI simulation, the variation pattern of deflection has been obtained. The deflection becomes higher with the decrease of driving height initially, and it decreases after reaching the peak with the lower driving height. This aeroelastic deflection causes the change of the angle of attack (AOA) partially, leading to a distinct performance comparing to the ideal model. It is worth to note that, the deflection is marginal due to the low inlet velocity setting, which may cause inaccurate prediction in high-velocity circumstance [4].

3.3. Aerodynamic performance

Drag increases with the decreasing of driving height, but the drag coefficient (C_D) gains a growth in any driving height if the aeroelastic behaviour is included. The induced drag increases due to the elastic deflection, and this could elucidate the phenomenon mentioned above. At the same time, lift coefficient (C_L) decreases continuously with the reduction of the driving height, which means that

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downforce increases in this process, and this phenomenon could be explained by the ground effect. Besides, wake and vortex structure is changed as a result of aeroelastic deformation, affecting aerodynamic performance of the front wing [4].

4. Aerodynamic interaction between F1 front wing and wheels

4.1. Models and simulation methods

There are several researches take attempts to explore the rules of aerodynamic interaction between F1 front wing and wheels. All studies use RANS equation as fundamental mathematics method. Daniel Martins and his team employ Spalart-Allmaras model as the solution of RANS equation and Detached-Eddy Simulation (DES) [5], while other researches take SST k - ω into account.

4.2. Aerodynamic interaction and flow characteristics

Researchers investigate the interaction between optimized front wing and wheels, showing a position change of vortex, which may improve the performance of controlling airflow distribution and reduce drag by dragging the wake of front wing [2]. Higher AOA of flap causes higher wheel drag with shorter and scattered wheel wake, as a result of radical flap setting which improves the strength of upwashing airflow and delays of separation point on the top of the wheel. As a valuable tool to control the wake of wheels, the vortex could be affected considerably by setting of wing and the interaction of the following structures [5]. Rotating wheels gains lower drag and lift than stationary wheels, and the rotating wheels lead to a lower aerodynamic load on the front wing, showing the necessity of simulation with front wing and following components [6]. A team discussed the influence of wake of wheels after installing the Gurney Flap (GF), and the outcome is remarkable. The wake of wheels is reduced evidently by the airflow interaction between of the front wing with a GF and suspensions [7]. According to the researches mentioned above, the interaction between front wing and wheels cannot be neglected, and rotating wheels play a significant role in the study of wake and actual performance of the front wing.

5. Front wing performance enhancing devices

5.1. CFD simulation models and analyse model

Researchers use SST k - ω model to find the solution of RANS equation in order to analyse the improvement of introducing the GF, which is a small structure on the trailing edge of the front wing. The inlet velocity of this research is set as 70 m/s [7]. Another study focuses on the AOA of the detached passive flap by setting flap's AOA at 16°, 18°and 20°. The inlet airflow velocity of first study is 70 m/s (approximately 252 km/h), while the airflow velocities of another are 250 km/h, 275 km/h, 300 km/h and 350 km/h [8].

5.2. Aerodynamic improvement after introducing the gerney flap

Drag and downforce improve more than 20% with a slight decrease of aerodynamic efficiency after employing the GF, and drag of wheels becomes lower. Downforce on the flap and endplate gain a higher increase than the main wing, but the main wing is the component with a evidently declining drag, showing the uniqueness. Higher airflow velocity occurs under the front wing when the GF is applied, causing a strong pressure zone and leading to the ground effect, which is related to higher

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downforce. Faster velocity along the suction side result in a smaller wake behind the front wing, lower drag could be explained by this phenomenon [7].

5.3. Aerodynamic performance of passive flap in a series of different condition

By setting AOA of flap at 16°, 18°and 20°, the relationship between downforce, drag and velocity maintain a relatively consistent in all inlet velocity condition. At various velocities, by increasing AOA from 16° to 20°, the growth rates of downfoce and drag maintain about 8.7% and 20% respectively [8].

6. Aerodynamic analysis of unexpected scenarios on the race track

6.1. Background and CFD simulation

Wheel-to-wheel is a common scenarios usually happen on the circuit, meaning two or more racing car side by side competing for the higher position. In this case, the lateral wake of one car affects the inlet airflow of another car, leading to a worse performance of front wing and other aerodynamic components. Inlet velocity is set at 45.3 m/s with a three-dimensional meshing setup based on the two-dimensional case. Due to the limitation of computational cost, the nose cone of front wing is neglected, which may influence the performance and accuracy negatively [9]. Endplates are significant and necessary component of a front wing, but it might be broken and lost accidentally due to aggressive driving and competing. Researchers test a front wing with and without endplates on the straight (320 km/h) and medium-speed corner (180 km/h with an airflow angle of 20°) to prove the necessity of endplates and changing the front wing if endplates are broken [10]. Both researches use SST k - ω model as the solver.

6.2. Aerodynamic performance analysis

By setting a ratio which reflects the direction of free stream, the front wing based on the FIA 2026 regulation shows a lower outwash airflow than the front wing from 2024 (based on the FIA 2022 regulation). This proves that the 2026 front wing could reduce lateral wake and enhance the competitiveness of the race. It is worth to note that, higher drag occur on the 2026 front wing since more inwash airflow causes strong recirculation [9]. Endplates play a necessary role in creating vortex which interacts with the wake of wheels. So the loss of endplates results in higher lateral forces and drag with lower downforce, causing a slight benefit on the straight but also an unsteady and uncontrollable scenarios at the corner. This is the reason why changing the fail front wing in the race is necessary although it leads to additional time loss by pit stop [10].

7. Different type of large eddy simulation on aerodynamic performance of f1 front wing

7.1. Two paths of Large Eddy Simulation (LES)

LES as a high accuracy simulation method, showing a strong capacity in dealing with complicated flow field, specifically for the F1 front wing. Explicit LES (eLES) is based on the Vreman subgrid-scale model and Implicit LES (iLES) is the extension of Kennedy Gruber kinetic energy preserving formulation in order to improve the robustness. Both approaches mentioned above are built upon high-order discontinuous Galerkin (DG) solver Horses 3D in order to obtain precise turbulent flows [11].

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7.2. Result and comparison of eLES and iLES

All factors acquired by both methodologies including pressure coefficient, skin friction coefficient, average momentum deficit and so forth that might affect aerodynamic performance demonstrate high consistency when they are compared to the solution of Nektar ++, while the turbulent kinetic energy (TKE) resulted from iLES shows a overestimation than the result of iLES and Nektar ++. The iLES has larger maximum stable time step, saving around 50% computational time cost with relatively precise solutions. Therefore, iLES gains more advantages than eLES due to lower time cost and better robustness in dealing with complex airflow field of the F1 front wing [9].

8. Conclusion

This review systematically organizes advanced researches in terms of F1 front wing. Initially, optimization of airfoil by employing adjoint methodology based on the parametric approach demonstrates an ability of striking the balance of drag and downforce, while the interaction between airflow of the front wing, wheel and surrounding components affects the aerodynamic performance impressively. FSI approach offers a more accurate prediction on the race track, due to high-velocity inlet airflow could change the AOA of components of the front wing marginally, which leads to a non-idealized performance of aerodynamic components. Besides, as one of drag contributors, wheels influence airflow field significantly, and rotating wheels become a necessity setup in order to find preciser solutions. Both downforce and drag could be affected by the additional Gurney Flap and detached passive flap. The GF also plays a role in controlling wake of wheels, while the downforce and drag induced by passive flap displays a constant regularity with the AOA of it and the velocity of the racing car. Moreover, by the comparison of 2024 and 2026 F1 front wing, limited outwash of 2026 regulation has been proved, which improves the motivation and possibility of overtaking. Endplates are essential in creating vortex and the lateral-force could be reduced, this is the reason why the front wing with broken or fail endplates should be replaced. Furthermore, the superiority of iLES has been verified, which is suitable for computing complicated airflow of the F1 front wing. Through the collation of studies, limited computational resources and ignorance of interaction between the front wing and surrounding components lead to inaccurate and impractical analysis. Therefore, the preservation of as many relevant structures as possible is one of approaches could be take into consideration. Although this is time-costing, holistic research, development and analysis are still crucial to conduct.

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