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CFD Investigation of Flap Deflection Angle Effects on the Downforce of a Two-Element FSAE Front Wing

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Abstract. Formula SAE (Society of Automotive Engineers) vehicles usually operate under low-speed cornering conditions, where the front wing is required to generate stable downforce to improve tire grip and handling performance.This paper investigates the effect of flap deflection angle on the downforce of a simplified two-element FSAE front wing using computational fluid dynamics. The simulations were conducted in STAR-CCM+ at a freestream velocity of 60 km/h with a steady incompressible RANS (Reynolds-averaged Navier-Stokes) approach with the k-ε turbulence model. The main element angle, slot gap, and overlap were kept constant, while four flap deflection angles of 0°, 20°, 40°, and 60° were analyzed. The results show that the downforce first increases and then decreases as the flap angle rises. The maximum downforce is achieved at 40°, while a further increase to 60° causes significant flow separation on the flap suction surface and reduces the aerodynamic performance. Therefore, the flap angle of a two-element FSAE front wing should be designed to balance downforce generation against stall prevention.

Keywords: Formula SAE, two-element front wing, flap deflection angle, downforce, CFD (Computational Fluid Dynamics)

1. Introduction

FSAE (Formula Society of Automotive Engineers) and Formula Student competitionsmainly consist of low- to medium-speed dynamic events, such as acceleration, skidpad, autocross, and endurance. Under these conditions, vehicles are particularly sensitive to the improvement in tire grip and steering response brought by aerodynamic downforce. The front wing is located at the foremost part of the vehicle. It not only directly affects the front axle load, but also influences the quality of the inflow to the undertray, radiators, and rear wing. Zhang and Zerihan reported that a racing car front wing usually operates in ground effect and can generate about 25–30% of the total downforce of the car. They also noted that the wake generated by the front wing strongly affects downstream components, including the undertray, diffuser, radiators, and rear wing [1]. Therefore, the front wing remain a key component in the low-speed aerodynamic development of Formula Student cars.

Wordley and Saunders developed an initial aerodynamic package for a Formula SAE car and emphasized that the aerodynamic package should produce maximum downforce while keeping the increase in drag and the reduction in top speed within acceptable limits [2]. In a companion study, they further developed and validated a high-downforce Formula SAE aerodynamic package using

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numerical methods, wind tunnel testing, and on-track testing [1]. Zhang and Zerihan investigated a double-element wing in ground effect and found that aerodynamic performance is strongly affected by ground proximity and flap setting. For large flap angles, downforce can drop sharply after reaching the maximum value because of boundary layer separation and circulation breakdown on the main element [2].

Based on the above research, this paper employs CFD (Computational Fluid Dynamics) simulation to investigate the aerodynamic performance of a simplified two-element FSAE front wing under a representative low-speed operating condition. Four flap deflection angles, namely 0°, 20°, 40°, and 60°, are compared at a freestream velocity of 60 km/h. The purpose of this study is to identify the relationship between flap angle and downforce, determine the approximate angle range at which peak downforce occurs, and explain the downforce reduction caused by flow separation. The results are expected to provide reference value for static flap angle selection and early-stage aerodynamic design of Formula SAE front wings.

2. Literature review

2.1. Operating condition selection

Compared with professional high-speed racing cars, FSAE cars mainly operate in low-speed corners and short straight-line sections. Gupta and Saxena reported that the representative operating speed range of a Formula SAE vehicle is approximately 15–20 m/s [3]. Since 60 km/h is equal to 16.67 m/s, this velocity lies within the typical Formula SAE operating range. Kirchberger also used 15 m/s as a representative operating speed in a Formula Student CFD validation study and stated that the flow can be considered incompressible within this speed range [4]. Therefore, it is reasonable to select 60 km/h as the baseline simulation condition is reasonable for analyzing the front wing behavior under representative FSAE competition conditions.

The low-speed nature of Formula Student also affects aerodynamic design philosophy. Hokkanen pointed out that Formula Student cars rarely exceed 100 km/h and that the track is almost constantly turning. Therefore, many teams focus on high downforce even at the cost of increased drag [5].

2.2. Flap deflection angle selection

In a two-element wing, increasing the flap angle generally increases the effective camber and pressure difference, which can enhance downforce within a certain range. However, this increase does not continue indefinitely. When the flap angle becomes too large, the adverse pressure gradient on the suction surface increases significantly. The boundary layer may then lose momentum and separate from the surface. Smith explained that the slot between elements in a multi-element wing can delay separation through mechanisms such as the slat effect, circulation effect, pressure-recovery improvement, and fresh-boundary-layer effect [6]. Zhang and Zerihan also showed that under a high flap-angle condition, downforce may decrease significantly beyond the maximum, owing primarily to boundary layer separation [2].

Therefore, the selected flap angles of 0°, 20°, 40°, and 60° form a parametric sweep that, while coarse, covers the entire trend of interest. The 0° case provides a baseline condition with low flap deflection. The 20° case represents a moderate deflection angle, at which the flow is expected to remain mostly attached and downforce should increase. The 40° case represents a high but still effective flap angle, at which the two-element wing may reach its maximum downforce. The 60° case represents an excessive flap angle, at which strong separation is expected. This angle range is

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suitable for observing the full trend from low downforce to peak downforce and then to stall-induced performance loss.

2.3. Turbulence model selection

Gupta and Saxena compared different turbulence models and finally selected the realizable k-ε model for Formula SAE vehicle external-flow analysis [6]. For a preliminary parametric study such as the present work, k-ε is suitable because the main objective is to compare the overall downforce trend under different flap angles rather than resolving all unsteady vortex structures in detail. However, the k-ε model has limitations in predicting strong adverse pressure gradients and large-scale separated flow. Menter's SST model is generally more suitable for adverse-pressure-gradient boundary layers and separated-flow prediction [7]. Therefore, future studies may compare k-ε and k-ω SST for critical stall cases.

3. Methodology

This study employed a CFD-based numerical simulation method. The simulations were carried out using Siemens STAR-CCM+. The research object was a simplified two-element FSAE front wing that consisted of a main element and a flap.

After the wing geometry was imported into STAR-CCM+, an external-flow computational domain was created around the model. To reduce the influence of far-field boundaries, the domain was kept sufficiently large around the front wing. The inlet was defined as a velocity inlet, while the outlet was defined as a pressure outlet. The ground plane was modeled as a moving wall moving at the same velocity as the incoming flow to represent the relative motion between the car and the road. The wing surfaces were defined as smooth no-slip walls.

The mesh was generated with local refinement around the wing surfaces, leading edges, trailing edges, and slot region. The slot region was refined because it plays an important role in controlling the flow over the flap suction surface. Boundary layer mesh was generated near the wing surfaces to improve the near-wall flow resolution. The purpose of the mesh setup was to capture the pressure distribution, velocity field, and separation behavior around the two-element wing.

The downforce was calculated by integrating pressure and shear stress over the wing surfaces. Four simulation cases were designed according to flap deflection angle: 0°, 20°, 40°, and 60°. In all four cases, the main element angle, slot gap, overlap, inlet velocity, domain size, mesh strategy, and boundary conditions were held constant.

The solution was monitored through residuals and aerodynamic force convergence. The simulation was considered converged when the residuals dropped to sufficiently low levels and stabilized, and when the downforce value reached a stable plateau during the final iterations. After convergence, downforce, pressure contours, velocity contours, and streamline patterns were extracted for comparison.

4. Results and discussion

As shown in Figure 1, the downforce of the two-element front wing increases initially and then decreases as the flap deflection angle increases. The downforce rises from approximately 1.3 N at 0° to about 5.5 N at 20°, and then reaches the maximum value of approximately 13.3 N at 40°. However, when the flap angle is further increased to 60°, the downforce decreases to about 10.5 N.

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These results indicate that increasing the flap deflection angle can improve downforce within a certain range, but an excessive flap angle leads to aerodynamic performance loss.

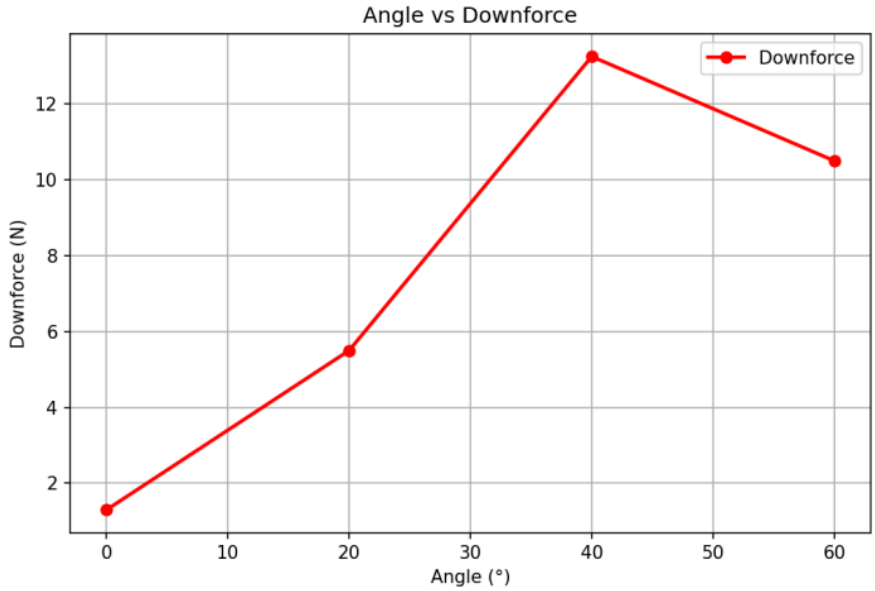

Figure 1. Variation of downforce with flap deflection angle

The variation in downforce can be explained by the combined effect of flap loading, boundary layer behavior, and the slot flow between the main element and the flap. When the flap deflection angle increases from 0° to 40°, the effective camber of the two-element wing increases, resulting in a stronger pressure difference between the suction side and the pressure side. Meanwhile, the slot jet helps re-energize the boundary layer on the flap suction surface and delays flow separation. Therefore, the flow remains mostly attached at moderate flap angles, allowing the downforce to increase and reach its maximum at 40°.

However, when the flap angle is further increased to 60°, the adverse pressure gradient on the flap suction surface becomes too strong. The boundary layer loses momentum and can no longer remain attached to the surface. As a result, large-scale flow separation occurs on the flap, which weakens the low-pressure region and reduces the total pressure difference across the wing. This explains why the downforce decreases sharply at 60° despite the larger flap deflection angle. These results indicate that the slot effect can delay stall to some extent,but it cannot fully prevent separation when the flap angle exceeds the critical value.

The pressure contours show that the low-pressure region on the suction side becomes stronger as the flap angle increases from 0° to 40° (Figure 2). This explains why downforce increases in this range. At 40°, the two-element wing benefits from both increased effective camber and the slot effect. The slot between the main element and the flap guides the flow toward the flap suction surface and helps maintain attached flow. As a result, the pressure difference between the upper and lower surfaces reaches its maximum among the tested angles.

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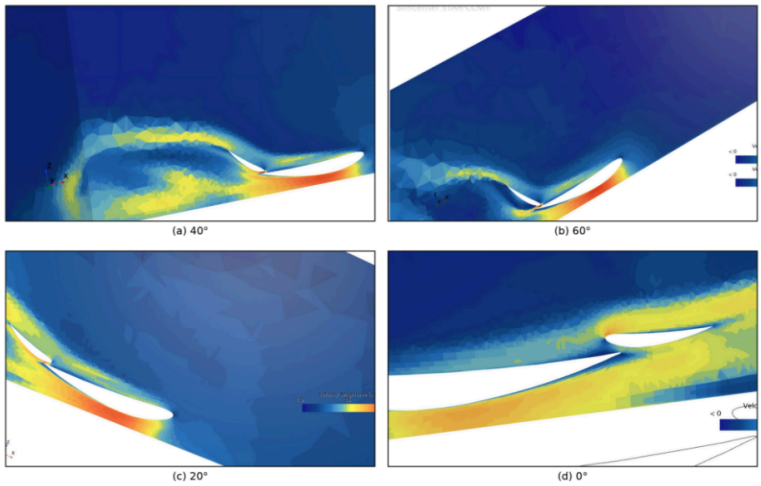

Figure 2. Velocity magnitude distributions around the two-element front wing under different flap deflection angle conditions: (a) 40°, (b) 60°, (c) 20°, and (d) 0°

However, the 60° case shows a different flow behavior. At such a large flap deflection angle, the adverse pressure gradient over the flap suction surface becomes too strong. The boundary layer near the wall loses momentum and can no longer remain attached to the surface. As a result, large-scale flow separation occurs on the flap suction side. This separation weakens the low-pressure region and reduces the pressure difference across the wing elements, causing a reduction in downforce. This is consistent with Zhang and Zerihan's finding that a high flap angle can lead to sharp downforce reduction after the maximum value is reached because of boundary layer separation and circulation breakdown [2].

The streamline and velocity contour results further support this explanation. For the 20° and 40° cases, the flow over the flap remains relatively organized, and the slot flow helps delay separation. In contrast, the 60° case shows disturbed streamlines, an enlarged recirculation region, and a thicker wake. This indicates that the slot effect has a limited flow-control capability. Although the slot can delay stall at moderate flap angles, it cannot fully prevent separation when the flap angle becomes excessive.

For practical FSAE front wing design, the 40° case can be considered the best-performing configuration within the tested range. However, it should not be adopted directly as the final design angle without further validation. In real racing conditions, the front wing is affected by ride-height variation, pitch motion, yaw angle, wheel wake, suspension interference, and unsteady airflow. Therefore, a flap angle slightly below the critical angle may be safer in practical design. For example, a refined simulation range around 35°-38° could be used to search for a more robust design point.

5. Conclusion

With STAR-CCM+, steady incompressible RANS simulations were performed at a freestream velocity of 60 km/h with the k-ε turbulence model. Four flap deflection angles, namely 0°, 20°, 40°, and 60°, were compared to evaluate their effects on downforce generation and flow separation behavior. This result supports the initial assumption that increasing the flap angle can improve downforce only within a certain range, beyond which stall effects become dominant.

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This research provides a focused CFD-based analysis of flap angle selection for a simplified two-element FSAE front wing, thereby supplementing the existing literature on this topic. The findings support and extend previous aerodynamic theories, providing evidence that while the slot effect can delay flow separation at moderate flap angles, but its ability to maintain attached flow becomes limited when the flap angle is excessively large.

From a practical perspective, this study has significance for the preliminary aerodynamic design and setup of FSAE front wings. In practice, a flap angle slightly below the critical value is recommended to provide a safety margin against changes in ride height, pitch motion, yaw angle, and unsteady airflow during actual racing conditions.

However, this study is limited in several aspects. First, only a simplified two-element front wing model was considered, while endplates, wheels, suspension components, and full-vehicle aerodynamic interactions were not included. This may limit the generalizability of the findings to a complete FSAE car. Second, the simulations were conducted only at a single freestream velocity of 60 km/h and only four flap angles were tested. As a result, the exact optimum flap angle and the precise stall boundary could not be determined. Third, the use of steady RANS with the k-ε turbulence model provides reasonable computational efficiency for preliminary analysis, but it may have limitations in predicting strong separation, complex vortical structures, and unsteady flow phenomena. In addition, the numerical results were not validated through wind tunnel or on-track experiments.

Future research should focus on improving the accuracy and applicability of the present study. A finer flap angle sweep, especially within the range of 30° to 45°, would help identify the optimum angle more precisely. Further simulations could also include different ride heights, pitch angles, yaw angles, and wheel rotation to better represent real racing conditions. In addition, comparisons between the k-ε and k-ω SST turbulence models would be useful for critical cases near stall. Wind tunnel testing or on-track pressure and force measurements would also be valuable for validating the CFD results.

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