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A Review on Yaw Angle Aerodynamics of NACA0015 Aerofoil Under Transient RANS Modeling for Formula Student Vehicles

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Abstract

Yaw based aerodynamic condition plays a critical role in the behavior of Low Reynolds Number aerofoils used in front wing applications of Formula Student vehicles. The symmetric NACA0015 profile is widely used in student motorsports for its manufacturability, predictable aerodynamics, and significant performance under inflow conditions. This review closely knits experimental, numerical, and theoretical findings related to yaw angle aerodynamics with particular emphasis on transient Reynolds Averaged Navier Stokes (RANS), Unsteady RANS (URANS), and Large Eddy Simulation methodologies. Key aerodynamic functions of laminar separation bubbles, side separations, crossflow vortex, and wake responses are examined. Additionally, comparative evaluation of turbulence models demonstrates that the k-ω Shear Stress Transport (SST) model remains the standard for yaw calculation, while LES and hybrid RANS-LES methods showed superior vortex based flows. The review identifies gaps in modeling for Low Reynolds Number aerofoils in yaw angle conditions, where it is needed for steering stability and cornering performance.

Keywords
NACA0015, Yaw Angle, RANS, Low Reynolds Number, Formula Student.

1. Introduction
Aerodynamic performance has become an important part of Formula Student vehicle design, where front and rear wings are used to generated downforce, improve tire grip, and enhance cornering performance without occurring drag penalties on track. Formula Student vehicles typically operate at relatively low speeds and short chord lengths, which

place front wing aerofoils in the low to moderate Reynolds Number conditions (Re $\approx 1 \times 10^5$ to 6×10^5). In these conditions, the laminar separation bubbles and early transitions strongly influence the overall aerodynamic efficiency (Buğday, 2025; Ibren et al., 2021).

Under real driving conditions, the flow approaching the front wing is rarely aligned with the vehicle longitudinal axis. During cornering, braking into a turn, steering inputs, and crosswind exposure; the vehicle experiences a yaw angle relative to the incoming flow. This yaw angle modifies the effective angle of attack and introduces a crossflow component that produces asymmetric pressure distributions on the aerofoil surface. As a result, the frontier side of the aerofoil experiences increased attached flow while the side portrays intensified pressure gradients, and earlier separation (Gao et al., 2023; Li et al., 2019).

The NACA0015 aerofoil has been extensively studied in modern CFD and experimental research because of its symmetric profile, moderate thickness, and suitability for both drag and downforce configurations. Studies on NACA0015 have showed laminar separation bubble formation, stall control, and the performance of different turbulence and transient models (Pack Melton et al., 2008; Obeid et al., 2017; Ibren et al., 2021; Catalano et al., 2024). However, most of these works focus on aligned inflow, with yaw effects often neglected indirectly. Meanwhile related studies on yaw movement aerofoils have demonstrated unsteady behavior and showed good lift and drag (Kouser et al., 2024; Gao et al., 2023; Cheng et al., 2015). And these are highly relevant to transient cornering maneuvers in Formula Student applications.

Recent work by (Madha et al., 2024) on automotive aerodynamics and Formula Student aerofoil behavior has further emphasized the need of understanding the performance under realistic environments. Their work on automotive aerodynamic drag and lift using CFD tools and the comparative study between SD7032 and NACA0015 aerofoils as rear wing for Formula Student cars illustrates how aerofoil selection influences downforce, drag, and wake stability across angles of attack (Madha et al., 2025), but yaw effect remains an open topic of these systematic studies.

1.1 Focus on NACA0015 Aerofoil

The NACA0015 profile is a symmetric aerofoil with 15% thickness to chord ratio, commonly used as a profile in low speed and Low Reynolds Number aerodynamic investigations, illustrated in Figure 1. Recent studies have explored its flow behavior over a broad range of angles of attack using RANS and LES models, identifying leading edge separation, laminar bubble formation, and stall characteristics that depend sensitively on Reynolds Number and surface conditions (Buğday, 2025; Ibren et al., 2021; Obeid et al., 2017).

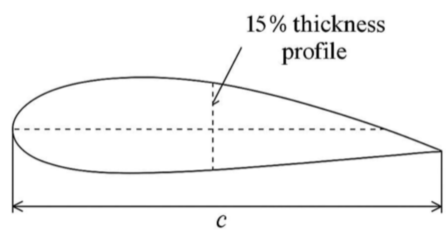

Figure 1. Geometry of NACA0015

For Formula Student applications, the NACA0015 is often inverted and used as a downforce generating element in both front and rear wing setups. Its symmetry simplifies design and relatively thick profile helps maintain stiffness. However, the same characteristics that make NACA0015 convenient lead to flow behavior that is under yaw when laminar separation bubbles enlarge and detach on the side of the wing.

1.2 Yaw in Formula Student Aerodynamics

In racing environments yaw angles typically range from a few degrees up to about 15° during cornering or under cross wind conditions, through larger effective yaw can occur when the vehicle experiences slip angles. Experimental and Numerical work on yaw based aerofoils, including symmetric sections, has shown that unsteady yaw produces lift, drag, and moment coefficients. These loops widen with increasing yaw amplitudes and frequencies (Gao et al., 2023; Li et al., 2019). For Formula Student vehicle's transient behavior, it can directly influence the effective aerodynamic balance and thereby affect driver confidence and lap time consistencies.

1.3 Objectives

1. Summarize most recent research on NACA0015 aerofoil behavior relevant to yaw based flow asymmetry, focusing on low to moderate Reynolds Number conditions.
2. Evaluate transient RANS (k-ω SST), URANS, LES, and hybrid turbulence models for their ability to capture separation bubble dynamics, and unsteady yaw effects.
3. Organize and compare key studies into structured framework emphasizing aerodynamic lift, drag, separation, modelling approaches, and Formula Student relevance.
4. Fetch out implications for Formula Student front wing design and identify research opportunities for yaw based aerofoil conditions.

2. Literature Review

2.1 Low Reynolds Number NACA0015 Aerodynamics

Recent analysis has revisited NACA0015 aerofoils performance at Low Reynolds Numbers using modern Computational Fluid Dynamics (CFD) techniques. (Obeid et al., 2017) carried out RANS simulations with a k-ω model for NACA0015 with a trailing edge flap at $R = 10^6$, showing how flap deflection and angle of attack strongly modify lift, drag, and stall. Through their work in higher Re than typical Formula Student conditions, it demonstrates the feasibility of capturing key aerodynamic features using relatively affordable CFD setups.

(Ibren et al., 2021) investigated laminar separation bubble and flow topology of NACA0015 aerofoil at Low Reynolds Number using k-ω SST Model, revealing bubble growth, reattachment, and stall behavior as angle of attack increased. Their results show the presence of laminar separation bubbles on the suction side and highlight the critical role of transition and separation in determining aerodynamic performance.

(Buğday, 2025) studied NACA0015 at Low Re in an aviation context, using CFD to map lift and drag performance over a wide angle of attack range. This work reinforces the importance of refining mesh density and numerical schemes to capture changes in boundary layer behavior at Low Reynolds Number aerofoils.

2.2 Laminar Separation Bubbles and Transition Modelling

The accurate prediction of laminar separation bubbles (LSB) remains a key challenge in Low Reynolds Number Aerofoil aerodynamics. (Crivellini et al., 2014) analyzed LSBs over Low Re aerofoils using RANS Modelling, emphasizing that bubble size and position are highly sensitive to transition modelling and turbulence closure. (Catalano et al., 2024) investigated LSB modelling on several aerofoils including NACA0015 using transitional URANS SST frameworks, showing that conventional turbulence models often mispredict bubble length.

(Giacomini & Westerberg, 2025) worked on different transition models for Low Re aerodynamic predictions, highlighting that precise capture of separation followed by reattachment is necessary to reproduce lift and drag curves observed experimentally. These findings showed that in yawed flow, where effective crossflow fluctuate, the bubble behavior may become even more complex.

2.3 Active and Passive Flow Control on NACA0015

Studies on active flow control strategies at Low Re have been tested on NACA0015 to delay stall and manipulate bubble dynamics. (Pack Melton et al., 2008) performed Low Re wind tunnel experiments on a NACA0015 with a trailing edge flap, using zero net mass flux to improve lift and delay stall compared to the uncontrolled case. (Tongsawang, 2015) examined stall control of NACA0015 at Low Re using hybrid RANS-LES model, showing improved prediction of separated flows and suggested that high fidelity methods are better suited for complex flow control scenarios.

2.4 Formula Student and Automotive Aerodynamics Context

Several works address aerodynamic optimization in motorsport and Formula Student. (Madha et al., 2024) presented a work on automotive aerodynamic drag and lift analysis using CFD tools, summarizing essential simulation practices and highlighting turbulence model selection and domain design for vehicle aerodynamics. In a later study (Madha et al., 2025) performed a comparative CFD analysis of SD7032 and NACA0015 aerofoils used as adjustable rear wing for Formula Student cars, demonstrating that different aerofoils produce significant drag and downforce within similar angles of attack.

Investigation and analysis on racing rar front wings and other related studies on motorsport aerodynamics further underline the impact of aerofoil geometry on balance and cornering stability, but yaw and transient effects are often simplified which leads to present this review's focus.

3. Review Methodology and Modelling Framework

This review focuses on aerofoil synthesis of recent works investigating NACA0015 and related symmetric NACA series aerofoils under low to moderate Reynolds numbers ($Re \leq 6 \times 10^5$), focusing literature relevant to yaw based aerodynamic behavior. The goal is to evaluate how contemporary CFD and experimental methods capture laminar separation bubbles, transition phenomena, separation asymmetry, and unsteady dynamics of Formula Student operating conditions.

3.1 Literature Identification and Screening

A structured search was conducted using Science Direct, SpringerLink, AIAA, MDPI, Wiley, AIP Publishing, IEOM Proceedings databases. Search terms included:

- NACA0015 Low Reynolds Number Aerofoil
- Laminar Separation Bubble NACA
- Yawed Aerofoil Aerodynamics
- Yaw Angle of Attack Aerodynamics
- NACA Airfoil LES
- NACA RANS
- Unsteady Transient Analysis
- Formula Student Aerofoil CFD

After a thorough search, studies among them were included if they satisfy:

- Recent publications (preferred within year 2000)
- Use of NACA0015 or symmetric NACA aerofoil with transient behavior
- Operating within low to moderate Reynolds number condition
- Application of RANS, URANS, DES, or LES methodologies of CFD
- Data includes aerodynamics coefficients, Cp distributions, separation characteristics, or flow information

3.2 Modelling Framework

Although this study did not perform new simulations. This study is an understanding of the equations and numerical frameworks for evaluating the predictive performance.

3.2.1 Reynolds Averaged Navier Stokes (RANS) and k-ω SST Model

Many studies were conducted using RANS formulation for fluid viscosity:

$$\frac{\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \partial p}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial {x_j}^2} - \frac{\partial (u_i{}' u_j{}')}{\partial x_j}$$

The k-ω SST model were implemented:

$$\nu_t = \frac{k}{\omega}$$

This model is used in NACA0015 studies of flow with pressure analysis by (Madha et al., 2025; Madha et al., 2024; Ibren et al., 2021; Obeid et al., 2017).

3.2.2 Transition URANS and Large Eddy Simulation (LES)
For Low Reynolds Number aerofoils, transition strongly influences aerodynamic coefficients. The Transition URANS introduces correlations to capture laminar turbulent transition. LES resolves the large scale turbulent structures directly:

$$\nu_t = (C_s \Delta)^2 |\bar{S}|$$

Here, Δ is the grid filter width.

(N. Counsil & Boulama, 2013) (Catalano et al., 2024) demonstrated that transitions can mispredict lift and drag. LES based studies of large scale structures with laminar separation bubble dynamics and wake instabilities were resolved more accurately than RANS models.

3.2.3 Yaw Implementation
Yaw angle β is used in two formations:

1. Rotating with velocity vector:

$$U_x = U_\infty \cos\beta, \quad U_y = U_\infty \sin\beta$$

2. Rotating geometry model:

$$\alpha_{eff} = \alpha_0 + \tan^{-1}\left(\frac{U_y}{U_x}\right) \approx \alpha_0 + \beta\,(\ll 1)$$

These experiments were conducted by (Gao et al., 2023; Li et al., 2019) for yaw motion.

3.2.4 Mesh
The Low Reynolds Number aerofoil requires:

1. $y^+ < 1$ near wall spacing
2. Leading edge clustering
3. Smooth mesh grading

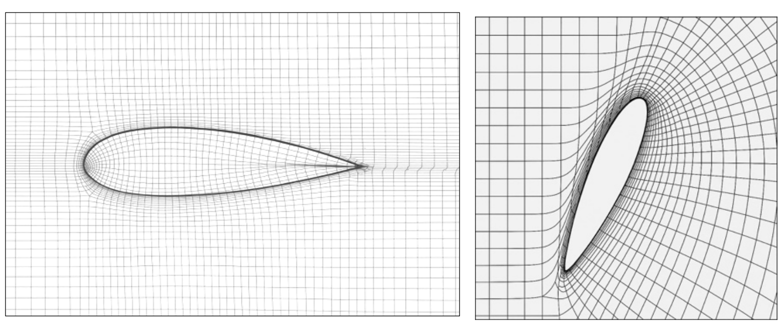

Figure 2. Meshing

A view of the mesh refinement around the aerofoil is presented in Figure 2, highlighting the inflation layers and leading-edge clustering used to maintain $y^+ < 1$ and to capture laminar separation bubble behavior.

4. Literature Data Extraction and Comparative Framework
The compiled key aerodynamic insights from NACA0015 and other symmetric aerofoil studies are explained here.

4.1 Comparative Study Set
After a thorough analysis, it includes:

1) Low Reynolds Number aerofoil with RANS simulation:
   a) (Buğday, 2025)
   b) (Ibren et al., 2021)
   c) (Obeid et al., 2017)

2) LSB focused works:
   a) (Giacomini & Westerberg, 2025)
   b) (Catalano et al., 2024)
   c) (Crivellini et al., 2014)
3) Flow control and LES/DES related studies:
   a) (Tongsawang, 2015)
   b) (Pack Melton et al., 2008)

4) Unsteady yaw based works:
   a) (Kouser et al., 2024)
   b) (Gao et al., 2023)
   c) (Li et al., 2019)

5) Formula Student aerofoil studies:
   a) (Madha et al., 2025)
   b) (Madha et al., 2024)

4.2 Mathematical Interpretation of Extracted Literature

1. Effective Re under yaw angle:

$$Re_{eff} = \left(\frac{\rho U_{\infty c}}{\mu}\right)(\cos\beta)$$

This finding matches the study conducted by (Catalano et al., 2024).

2. Pressure asymmetry:

$$C_p = p - p_{\infty}/\frac{1}{2}\rho U_{\infty}^2$$

This formula generates more negative Cp in upper side and less negative Cp, example showed in Figure 3 in the following.

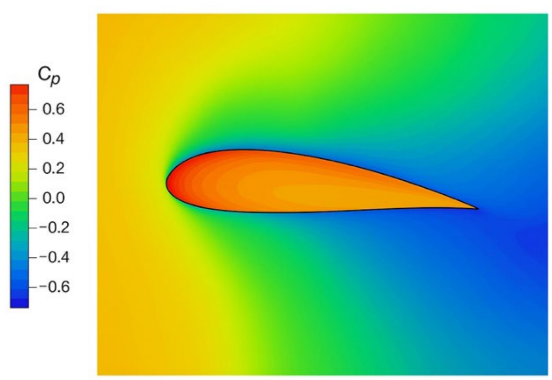

Figure 3. Cp Contour

3. Bubble Length Scaling:
Bubble length is inversely proportional to overall velocity with yaw effects:

$$L_{b,\beta} = \frac{L_{b,0}}{\cos\beta}$$

Li et al. (2019), Gao et al. (2023), and Catalano et al. (2024) observed bubble scaling and stall.

4. Vorticity Under Yaw:
The crossflow velocity leads to wake, vortex shedding, and asymmetric separation. The equation stands:

$$U_y = U_\infty \sin\beta$$

4.3 Narrative of Comparative Findings
Across these studies, several findings can be highlighted:
1. Reynolds Number Sensitivity: At the condition for Formula Student, Reynolds number ($Re \approx 1\times10^5$ - 3×10^5), bubble dynamics works better (Crivellini et al., 2014).
2. Modelling Approach: The k-ω SST model is good but underpredicts vortex intensity compared to LES (Catalano et al., 2024).
3. Flow Phenomena: Commonly found LSB formation, edge separation, and asymmetric wake deflection to yaw based cases.
4. Yaw Applicability: Direct yaw on NACA0015 aerofoil studies are limited. However, found yaw experiments (Li et al., 2019; Kouser et al., 2024) showed bubble separation, and nonlinear lift loss.

5. Reported Aerodynamic Results and Discussion
5.1 Aerodynamic Force Under Yaw Angle
Yaw inflow aerofoil studies (Li et al., 2019; Gao et al., 2023) showed that lift decreases and drag increases as yaw angle grows, with linear conditions at small yaw angles (up to around 8° - 10°) and nonlinear behavior at larger yaw angles due to massive separation. For a symmetric aerofoil like NACA0015 operating at low Re may expect:

- A reduction in effective negative lift as yaw increases
- Development of side force and yaw condition due to asymmetric pressure distribution

5.2 Turbulence and Transition Model Performance
RANS k-ω SST model, performed well in mean lift and drag under separated conditions (Buğday, 2025; Obeid et al., 2017). However, they may fail to capture fine scale unsteady structures that significantly impact yaw sensitivity. Transitional URANS and LES models better resolve laminar separation bubbles and unsteady vortices (Catalano et al., 2024; Kouser et al., 2024)

For Formula Student teams, an effective workflow would likely take:
1) RANS SST for initial design and parametric studies
2) Transitional RANS or URANS for improved stall and bubble prediction

5.3 Implications for Formula Student Front Wing Design
The findings in this review suggest the following implications for NACA0015 based front wings:

i. At low Reynolds number, the yaw effects are impacted by LSB dynamics, which may risk sudden downforce loss during cornering event
ii. Front wings should consider not only aligned flow performance but also off axis behavior and sensitivity to laminar separation bubbles
iii. NACA0015 in CFD workflow for Formula Student should incorporate at least some unsteady transient simulations of yaw changes during cornering effects

6. Conclusion
This review has studied recent works relevant to the yaw angle aerodynamics of the NACA0015 aerofoil under low to moderate Reynolds number conditions, focusing on computational and experimental findings that portray Formula Student front wing design. A very few studies confirm that NACA0015 is strongly affected by laminar separation bubbles, early stall, and unsteady vortex dynamics. While most work examines aligned inflow and related aerofoil studies that provide moderate yaw introduces significant asymmetry leading to lift loss, drag rise, and unsteady forces. RANS with k-ω SST remains the good modelling approach but exhibits limitations in capturing laminar separation

bubble dynamics and unsteady yaw effects. The URANS, LES, and hybrid RANS LES methods showed good results at higher computational calculation. For Formula Student applications, a combined CFD method is recommended by combining RANS based design. Overall, the NACA0015 research suggests that yaw based design and consideration of low Reynolds Number aerofoils are essential to achieve predictable aerodynamic performance in Formula Student front wings.

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References
Buğday, M. Aerodynamic performance analysis of NACA0015 airfoil at low reynolds numbers. *Havacılık ve Uzay Çalışmaları Dergisi*, 5(1), 65–85, **2025**, https://doi.org/10.52995/jass.1619615

Ibren, M., Andan, A. D., Asrar, W., & Sulaeman, E. Laminar Separation Bubble and Flow Topology of NACA0015 at Low Reynolds Number. *CFD Letters*, 13(10), 36–51, **2021**, https://doi.org/10.37934/cfdl.13.10.3651

Gao, R., Yang, J., Yang, H., & Wang, X. Wind-tunnel experimental study on aeroelastic response of flexible wind turbine blades under different wind conditions. *Renewable Energy*, 219, 119539, **2023**, https://doi.org/10.1016/j.renene.2023.119539

Li, G., Huang, X., Jiang, Y., & Qin, C. An experimental study of the dynamic aerodynamic characteristics of a yaw-oscillating wind turbine airfoil. *Physics of Fluids*, 31(6), **2019**, https://doi.org/10.1063/1.5088854

Pack Melton, L., Hannon, J., Yao, C.-S., & Harris, J. Active Flow Control at Low Reynolds Numbers on a NACA 0015 Airfoil. *26th AIAA Applied Aerodynamics Conference*, **2008**, https://doi.org/10.2514/6.2008-6407

Obeid, S., Jha, R., & Ahmadi, G. RANS Simulations of Aerodynamic Performance of NACA 0015 Flapped Airfoil. *Fluids*, 2(1), 2, **2017**, https://doi.org/10.3390/fluids2010002

Catalano, P., de Rosa, D., D'Alessandro, V., Marouf, A., Hoarau, Y., Miozzi, M., & Righi, M. M. The Adaptable and Resilient Safety System: The Human Factor in Future In-Time Aviation Safety Management Systems. *AIAA SciTech Forum*, **2024**, https://arc.aiaa.org/doi/10.2514/6.2024-1603

Cheng, J., Lowenberg, M. H., Wang, X.-M., & Yu, J.-Y. Wind Tunnel Wall Interference Effects on an Oscillating Aerofoil in the Stall Regime. *33rd AIAA Applied Aerodynamics Conference*, **2015**, https://doi.org/10.2514/6.2015-2717

Kouser, T., Kurtulus, D. F., Aliyu, A., Goli, S., Alhems, L. M., Imran, I. H., & Memon, A. M. Unsteady Aerodynamics Over NACA0005 Airfoil for Ultra-Low Reynolds Numbers. *IEEE Access*, 12, 83658–83674, **2024**, https://doi.org/10.1109/access.2024.3413153

Madha, J. M., Nawar, A., Rahman, M. M., & Akbar, N. I. Study on the Aerodynamic Effects of SD7032 Aerofoil as Adjustable Front Wings of a Formula Student Car. *IEOM Society*, **2024**, https://doi.org/10.46254/EU07.20240207

Madha, J. M., Niessner, J., & Koch-Gröber, H. A Comparative Numerical Aerodynamic Study between SD7032 and NACA0015 Aerofoil as Adjustable Rear Wing for Formula Student Cars. *6th African International Conference on Industrial Engineering and Operations Management*, **2025**, https://doi.org/10.46254/af6.20250151

Crivellini, A., D'Alessandro, V., Di Benedetto, D., Montelpare, S., & Ricci, R. Study of laminar separation bubble on low Reynolds number operating airfoils: RANS modelling by means of a high-accuracy solver and experimental verification. *Journal of Physics: Conference Series*, 501(1), 012024, **2014**, https://doi.org/10.1088/1742-6596/501/1/012024

Giacomini, E., & Westerberg, L.-G. CFD Analysis of Transition Models for Low-Reynolds Number Aerodynamics. *Applied Sciences*, 15(18), 10299, **2025**, https://doi.org/10.3390/app151810299

Tongsawang, K. Stall Control of a NACA0015 Aerofoil at Low Reynolds Numbers, **2015**.

Counsil, J. N., & Boulama, K. G. Low-Reynolds-Number Aerodynamic Performances of the NACA 0012 and Selig–Donovan 7003 Airfoils. *Journal of Aircraft*, **2025**, https://doi.org/10.2514/1.C031856

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