

# Research Progress and Prospects of Humpback-Whale-Inspired Leading-Edge Tubercles in Automotive Rear-Wing Aerodynamic Design

Jiahang Lyu\*

*Department of Mechanical Engineering, Southwest Jiaotong University, Chengdu, China*

*\*Corresponding author: Jiahang Lyu.*

---

## Abstract

Automotive rear wings operate in a three-dimensional, non-uniform flow field shaped by the vehicle wake, ground motion, supports, and yawed inflow. This review evaluates whether humpback whale-inspired leading-edge tubercles can provide useful passive flow control in this environment. Literature published mainly from 2021 to 2026 is organized through a mechanism-validation-transfer-focus framework. Fundamental studies show that tubercles generate streamwise vortices and divide full-span separation into localized peak-trough cells. Their most repeatable benefit is not a universal increase in maximum lift, but a smoother stall process, improved post-stall load retention, and, under selected unsteady conditions, reduced load coherence. These gains often involve a pre-stall efficiency penalty and depend strongly on amplitude, wavelength, Reynolds number, baseline airfoil, aspect ratio, and installation conditions. Cross-domain results from rotating machinery demonstrate engineering potential but cannot be transferred directly because rotation introduces centrifugal effects, periodic inflow, and distinct tip-vortex dynamics. Direct automotive evidence remains scarce, and a Formula 1 ground-effect study reported no efficiency improvement. Future work should therefore prioritize standardized operating-condition matrices, parameter interactions, and localized coverage, dynamic validation, and engineering robustness within a full-vehicle environment.

## Keywords

humpback-whale-inspired design, leading-edge tubercles, automotive rear wing, stall control, computational fluid dynamics, wind-tunnel testing

---

## 1. Introduction

An automotive rear wing is an inverted finite wing used to generate downforce with an acceptable drag penalty. Unlike an isolated two-dimensional airfoil, it operates in a flow field already modified by the vehicle body, rear-window separation, wheel and underbody wakes, supports, ground motion, and crosswind. Its local velocity and effective angle of attack, vary along the span. Results obtained from uniform-flow airfoil tests cannot be applied directly to an installed rear wing. This review asks whether leading-edge tubercles are suitable for such complex operating conditions and what evidence is required before an automotive design benefit can be claimed.

Engineering tubercles are usually represented by a sinusoidal leading edge defined by amplitude  $A$  and wavelength  $\lambda$ . Peak-trough pressure differences generate spanwise transport and counter-rotating streamwise vortices, which can prevent separation from developing simultaneously across the full span [1]. Recent experiments nevertheless show a recurring trade-off: pre-stall lift or efficiency may decrease while stall becomes more gradual and post-stall loading becomes more stable [2]. Parametric CFD studies further demonstrate that the outcome changes with geometry, Reynolds number, aspect ratio, and baseline airfoil [3,4]. Tubercles should therefore be treated as a condition-dependent separation-control device rather than a universal method for increasing lift and reducing drag.

The review focuses on airfoil-based automotive rear wings, including single- and multi-element devices on racing and high-performance road vehicles. Lip spoilers whose main function is to alter rear-body separation are discussed only when vehicle-wake coupling is relevant. The principal search window is January 2021 to July 2026. The discussion follows the sequence of biomimetic mechanism, cross-domain validation, automotive transfer, and rear-wing-focused research needs.

## 2. Biomimetic Mechanisms and Fundamental Airfoil Research

### 2.1 Biological Prototype and Flow-Control Principles

The leading edge of a real humpback whale flipper is not perfectly periodic, whereas most engineering studies use regular sinusoidal tubercles. As the flow passes a peak, local chord, curvature, and pressure gradient differ from those at the adjacent trough. The resulting transverse pressure difference drives spanwise flow and produces streamwise vortex pairs over the suction surface. These vortices mix higher-momentum fluid toward the wall, while the trough regions may experience earlier local separation.

The mechanism is better described as separation reorganization than as a generic increase in turbulence. Peaks act partly as vortex generators, troughs act as controlled initiation sites for separation, and the undulating edge shifts stall spatially along the span. The compartmentalization model proposed by Cai et al. suggests that streamwise vortices and transverse boundaries inhibit the spanwise merging of separated zones [1]. The relative importance of these effects changes with  $A/\lambda$ , leading-edge radius, Reynolds number, transition state, and finite-wing spanwise flow; consequently, no single vortex pattern explains all reported results [2,3].

### 2.2 Stall-Alleviation Performance and Four-Stage Flow Evolution

Across recent airfoil studies, the clearest benefits occur near and after stall. Wang et al. found that tubercled NACA 634-021 configurations showed slightly poorer pre-stall performance but a smoother stall and more stable post-stall loads [2]. Schmidt and Redonnet similarly reported a pre-stall penalty-post-stall benefit, with an intermediate  $A/\lambda$  giving the best compromise among the tested cases [5]. The aerodynamic evolution can be summarized in four stages.

*Table 1: Four-stage aerodynamic evolution of a tubercled leading edge*

| Flow stage               | Dominant response                                                                                          | Typical aerodynamic implication                                                                 |
|--------------------------|------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Low angle of attack      | Added wetted perimeter and three-dimensional mixing; vortices remain relatively weak.                      | Possible drag or lift-curve penalty with limited separation-control benefit.                    |
| Moderate angle of attack | Peak-generated vortices increase momentum exchange while trough adverse pressure gradients strengthen.     | Benefits and penalties become sensitive to $A/\lambda$ , Reynolds number, and baseline airfoil. |
| Near stall               | Localized trough separation develops while peak regions remain attached and inhibit spanwise merging.      | Full-span stall becomes less synchronous; load decline may become smoother.                     |
| Deep stall               | Organized vortices may preserve partial low-pressure regions and separated cells remain compartmentalized. | Post-stall load retention can improve, although peak load may be lower.                         |

This four-stage view explains why published conclusions may appear contradictory. A configuration can reduce the peak load yet improve stall margin or post-stall smoothness; another can raise  $C_{L,max}$  for a specific finite wing, but incur greater drag at the design point. For example, Bardera et al. reported an approximately 17% increase in  $C_{L,max}$  for one Eppler 186 configuration [4], whereas Wang et al.

emphasized stall alleviation after a lower peak load [2]. Peak performance, design-point efficiency, stall margin, and load smoothness are therefore separate objectives and should not be combined into a single claim of “stall delay.”

### 3. Cross-Domain Engineering Validation and Technology Transfer

#### 3.1 Adaptability under Dynamic Operating Conditions

Dynamic evidence is less extensive than steady evidence. Tubercled wings under pitching motion show changes in leading-edge separation, dynamic-stall-vortex formation, spanwise propagation, and load phase [6,7]. These findings support the more cautious conclusion that tubercles can modify the spectrum and coherence of unsteady loading; they do not guarantee higher mean aerodynamic performance in every dynamic condition.

IDDES calculations for a ducted propeller found that sufficiently large tubercles reduced the dominant-frequency peak of blade force, whereas smaller tubercles produced little change [8]. This result suggests a geometric threshold for unsteady effects. However, rotating blades experience centrifugal loading, rotation-induced flow, periodic inflow, and tip-vortex dynamics that are absent or substantially different on a fixed automotive rear wing. Rotating-machinery results can therefore motivate automotive measurements of load RMS, coherence, and power spectra, but they cannot be used as direct rear-wing design conclusions.

#### 3.2 Transferable Lessons from Rotating Machinery

Wind turbines, tidal-current turbines, turbine cascades, and propellers show that tubercle performance depends on operating point and is often most useful near adverse incidence or stall. Optimum amplitude varies with wind-turbine conditions [9,10], cascade benefits occur only over limited incidence ranges [11], and propeller gains are likewise confined to selected loading regimes [12,8]. The transferable lesson is operating-envelope sensitivity; the non-transferable factors include rotation, centrifugal and Coriolis effects, cyclic inflow, cavitation, and different tip-vortex dynamics. These studies demonstrate engineering potential but do not replace automotive validation.

### 4. Automotive Rear-Wing Evaluation Framework and Evidence

#### 4.1 Rear-Wing Flow Environment

A rear wing operates in a strongly non-uniform flow produced by the roof boundary layer, C-pillar vortices, diffuser, supports, endplates, ground motion, wheels, yaw, and pitch. Local velocity and incidence, vary across the span, so a uniform sinusoidal leading edge may not be optimal. A full-scale electric sports-car study without tubercles showed that airfoil selection, twist, angle of attack, and supports had to be co-designed for the three-dimensional rear-body inflow [13]. It also identified structural and flow-related frequencies. Tubercled-wing design must consequently treat the vehicle body and installation as integral parts of the aerodynamic system.

#### 4.2 Sign Convention and Performance Metrics

This review uses the aeronautical sign convention: positive lift acts upward, and automotive downforce is  $C_{DF} = -C_L$ . Stall is identified by a marked reduction or reversal in the growth of  $|C_L|$ , accompanied by large-scale separation; drag rise alone is insufficient. Core metrics are downforce, drag,  $C_{DF}/C_D$ , stall margin, balance, and yaw sensitivity. Dynamic work should also report load RMS, coherence, dominant frequency, and power spectral density, using consistent definitions of geometry and reference area.

#### 4.3 Direct Automotive Evidence

Public evidence directly applying leading-edge tubercles to an automotive rear wing remains almost absent. The closest recent automotive study examined a Formula 1 two-element front wing under ground effect. CFD and adjoint optimization varied tubercle frequency, amplitude, and ride height but found no improvement in aerodynamic efficiency within the investigated design space [14]. This null result is important because it shows

that ground effect, inter-element gaps, and installation interactions can eliminate benefits observed on isolated wings.

The current validation benchmark is instead provided by conventional rear-wing studies. Liu et al. combined full-scale CFD, full-vehicle wind-tunnel testing, realistic three-dimensional inflow, and separate rear-wing load measurements for an electric sports car [13]. A credible tubercled-wing study should reach at least this level: isolated-wing trends should first be validated, then re-tested with the vehicle wake, moving ground, rotating wheels, supports, and endplates included. Until such a chain is completed, evidence from airfoils, UAV wings, or rotating machinery should be described as transferable hypotheses rather than direct proof of automotive benefit.

## 5. Discussion: Evidence, Parameters, and Research Gaps

### 5.1 Research Methods and Evidence Hierarchy

Research methods differ greatly in cost and engineering credibility. Their appropriate roles are summarized below.

*Table 2: Roles and limitations of principal research methods*

| Method                                    | Appropriate role                                                        | Main limitation for automotive transfer                                                             |
|-------------------------------------------|-------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| Two-dimensional steady RANS               | Rapid preliminary screening of $A/c$ , $\lambda/c$ , and incidence.     | Cannot represent wingtip flow, endplates, supports, or vehicle wake.                                |
| Three-dimensional steady RANS             | Minimum reasonable level for finite-wing parametric studies.            | Limited treatment of deep stall, hysteresis, and load spectra.                                      |
| URANS / DDES / LES                        | Mechanism and spectral analysis for representative unsteady cases.      | Sensitive to model choice, time step, sampling duration, and inlet turbulence.                      |
| Finite-wing and full-vehicle wind tunnels | Validation of forces, separation, transition, and installation effects. | Higher cost; scale, blockage, support interference, and measurement uncertainty must be controlled. |

A rational workflow, begins with economical screening, uses high-fidelity simulations only for representative cases, validates the mechanism on a finite wing, and ends with full-vehicle confirmation. Increasing numerical fidelity does not remove the need to report transition treatment, grid independence, sampling duration, inlet turbulence, and uncertainty.

### 5.2 Parameter-Dependent Performance Trends

Key variables include  $A/c$ ,  $\lambda/c$ ,  $A/\lambda$ , tubercle number, phase, leading-edge radius, and spanwise coverage. Stronger geometry can intensify streamwise vortices but also increase drag and early trough separation; no universal optimum exists [3]. Large-amplitude, short-wavelength designs can improve peak load for some finite wings [4], whereas intermediate  $A/\lambda$  may better balance pre- and post-stall performance [5]. Automotive results will additionally depend on the baseline airfoil, twist, endplates, supports, multi-element gaps, ride height, yaw, and local incidence, making localized or spanwise-varying coverage a promising design strategy.

### 5.3 Research Gaps

Four gaps dominate the automotive evidence base: realistic envelopes of speed, yaw, pitch, gusts, and wake interference are rarely tested; parameter studies seldom include localized coverage, phase, tolerances, twist, or endplates; synchronized pressure, force, structural, and wake measurements are lacking for installed wings; and robustness to rain, dust, damage, noise, and maintenance remains largely unknown. These gaps directly motivate the four research directions below.

## 6. Future Research Directions

### 6.1 Standardized Operating-Condition Matrix

A three-level matrix should progress from an isolated finite wing, to an installed wing with supports, endplates, ride-height effects, and non-uniform inflow, and finally to a complete vehicle with moving ground

and rotating wheels. Speed, yaw, pitch, and gusts should be swept, and effectiveness judged across the target envelope, including the worst-case penalty.

## 6.2 Parameter Interactions and Localized Coverage

Physics-informed design of experiments should map  $A/c$ ,  $\lambda/c$ , and incidence before adding localized coverage, spanwise variation, phase, twist, endplates, and multi-element gaps. Smooth controls must preserve the mean chord and projected area, while optimization should report sensitivity and manufacturing tolerance rather than only one optimum.

## 6.3 Dynamic Validation

Dynamic validation should combine unsteady CFD with simultaneous force, pressure, strain, and wake measurements. URANS can screen the envelope, while DDES or LES should target representative stall, gust, and preceding-vehicle-wake cases. The key test is whether tubercles reduce coherent full-span separation and fatigue rather than merely shift spectral energy.

## 6.4 Engineering Robustness

Final prototypes should be assessed under roughness, contamination, rain, damage, and manufacturing variation, together with noise, strength, mass, cleaning, and maintenance. Practical value requires an integrated benefit with no hazardous downforce loss in the worst condition.

## 7. Conclusions

Humpback-whale-inspired leading-edge tubercles reorganize separation through peak trough pressure differences, streamwise vortices, and compartmentalization. Recent evidence does not support universal simultaneous gains in lift, drag, and stall angle. A more defensible role is to exchange some pre-stall efficiency for smoother stall, stronger post-stall load retention, or lower coherence under selected conditions. Performance depends on geometry, Reynolds number, baseline airfoil, finite-wing flow, and installation. Cross-domain studies show potential but cannot replace automotive evidence, while the Formula 1 ground-effect null result confirms that installation can remove isolated-wing gains [14]. A staged program of screening, finite-wing experiments, and full-vehicle validation is therefore essential.

## References

- [1] CAI C, ZHOU T, LIU S, ZUO Z, ZHANG Y, LI Q. Modeling of the compartmentalization effect induced by leading-edge tubercles[J]. *Physics of Fluids*, 2022, 34(8): 087104. DOI: 10.1063/5.0098400.
- [2] WANG D, CAI C, ZHA R, et al. Impact of leading-edge tubercles on airfoil aerodynamic performance and flow patterns at different Reynolds numbers[J]. *Energies*, 2024, 17(21): 5518. DOI: 10.3390/en17215518.
- [3] LUO D, LU B, BAI Y, YANG H. CFD analysis of the aerodynamic performance of airfoils with leading-edge tubercles: A parametric investigation[J]. *Ocean Engineering*, 2025, 331: 121311. DOI: 10.1016/j.oceaneng.2025.121311.
- [4] BARDERA R, RODRÍGUEZ-SEVILLANO Á A, BARROSO-BARDERAS E, MATÍAS-GARCÍA J C. CFD study of the effect of leading-edge tubercles on the aerodynamic characteristics of a small UAV based on Eppler 186 airfoils[J]. *Results in Engineering*, 2024, 23: 102639. DOI: 10.1016/j.rineng.2024.102639.
- [5] SCHMIDT T G, REDONNET S. Exploring a bio-inspired passive flow control strategy for wind turbines: Experimental characterization of the aerodynamics of a wind turbine blade section possibly equipped with leading-edge tubercles[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2024, 250: 105768. DOI: 10.1016/j.jweia.2024.105768.
- [6] ZHAO M, XU L, TANG Z, et al. Onset of dynamic stall of tubercled wings[J]. *Physics of Fluids*, 2021, 33(8): 081909. DOI: 10.1063/5.0057730.

- [7] ZHAO M, XU L, LI X, ZHAO Y, LIU Z. Dynamic stall of pitching tubercled wings in vortical wake flowfield[J]. *Physics of Fluids*, 2023, 35(1): 015122. DOI: 10.1063/5.0134109.
- [8] ZHANG X D, CAO L S, WAN D C. Wake-instability analysis of a ducted propeller fitted with leading-edge-tubercled blades[J]. *The Ocean Engineering*, 2023, 41(2): 73–85. DOI: 10.16483/j.issn.1005-9865.2023.02.008. (in Chinese)
- [9] KE W, HASHEM I, ZHANG W, ZHU B. Influence of leading-edge tubercles on the aerodynamic performance of a horizontal-axis wind turbine: A numerical study[J]. *Energy*, 2022, 239: 122186. DOI: 10.1016/j.energy.2021.122186.
- [10] BENAVIDES ZADOROZHNA D, BENAVIDES O, SIERRA GRAJEDA J, FIGUEROA RAMIREZ S, DE LA CRUZ MAY L. A parametric study of the effect of leading edge spherical tubercle amplitudes on the aerodynamic performance of a 2D wind turbine airfoil at low Reynolds numbers using computational fluid dynamics[J]. *Energy Reports*, 2021, 7: 4184–4196. DOI: 10.1016/j.egyr.2021.06.093.
- [11] DUAN W, CHEN W, ZHAO X, QIAO W. Numerical studies on the effect of leading edge tubercles on a low-pressure turbine cascade[J]. *Energies*, 2023, 16(11): 4398. DOI: 10.3390/en16114398.
- [12] FALCHI M, ORTOLANI F, SHI W, et al. Experimental investigation on the effect of leading edge tubercles on the performance of marine propellers in fully wet condition[J]. *Ocean Engineering*, 2022, 255: 111249. DOI: 10.1016/j.oceaneng.2022.111249.
- [13] LIU K, LUO Q L, WANG J Y, et al. Numerical and experimental investigation of the aerodynamic design of a rear wing for an electric sports car[J]. *Acta Aerodynamica Sinica*, 2026, 44(4): 152–162. DOI: 10.7638/kqdlxxb-2025.0047. (in Chinese)
- [14] TOPRAKOGLU F, OZYUMRUOGLU I, RANA Z A, DI PASQUALE D. Impact of whale tubercles on the aerodynamics characteristics of F1 front wing—Adjoint optimization[C]//AIAA SCITECH 2025 Forum. Orlando: AIAA, 2025: AIAA 2025-0479. DOI: 10.2514/6.2025-0479.

## Funding

This research received no external funding.

## Conflicts of Interest

The authors declare no conflict of interest.

## Acknowledgment

This paper is an output of the science project.

## Open Access

This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

