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# Effects of low-profile vortex generators on the aerodynamic efficiency of micro aerial vehicles

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## Abstract

This study examines how the aerodynamic performance enhancements in Micro Aerial Vehicles (MAVs) through the application of low-profile Vortex Generators (VGs) on rectangular wings. Computational simulations, employing the SST k-ω turbulence model at a Reynolds number of 100,000, were combined with the Response Surface Method (RSM) to determine the optimal VG configuration for enhanced performance at a 10° Angle of Attack (AOA). The results reveal significant improvements in boundary layer control, leading to delayed flow separation, increased lift, and reduced drag. Specifically, the optimized VG configuration reduced drag by 26% while moderately improving lift. These findings demonstrate the efficacy of VGs in enhancing MAV flight efficiency, offering a crucial solution for low-Reynolds-number aerodynamic challenges. This work contributes to the design optimization of MAV wings for better maneuverability and endurance.

**Keywords:** Aerodynamic Performance; Micro Air Vehicle; Rectangular Wing; Vortex Generators

## 1. Introduction

The advent of Micro Aerial Vehicles (MAVs) has significantly expanded the horizon of aerospace applications, especially in areas requiring agility, compactness, and enhanced maneuverability. These miniature flying platforms, typical characterized by wingspans of less than 15cm and Low Reynolds numbers, are utilized in diverse fields ranging from environmental monitoring and military reconnaissance to search and rescue operations. Despite their burgeoning utility, MAVs face considerable aerodynamic challenges due to their small size and low operating speeds, which necessitate innovative design solutions to optimize their performance. One such solution lies in the application of low-profile vortex generators (VGs), which have shown promising potential in enhancing the aerodynamic characteristics of MAVs.

Vortex generators are small aerodynamic devices that are strategically placed on the surface of an aircraft's wing to improve its aerodynamic performance. By creating controlled vortices, VGs energize the boundary layer, delaying flow separation, and thereby reducing drag and increasing lift. This mechanism is particularly beneficial for MAVs, which often struggle with premature flow separation due to their small size and low Reynolds numbers. Traditional vortex generators, however, can be intrusive and cause significant drag penalties, making low-profile VGs a more suitable alternative for MAV applications.

The concept of vortex generators to enhance aerodynamic performance is not new and has been extensively studied in the context of larger aircraft. However, the application of Low-profile VGs to MAVs presents unique challenges and opportunities. The small size and low speed of MAVs mean that the aerodynamic principles and behavior observed in larger aircraft do not directly translate. For instance, the Reynolds number, which is dimensionless quantity used to

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predict flow patterns in different flow situations, is significantly lower MAVs resulting in different flow characteristics and challenges.

VGs are passive devices to control flow which are able to change the motion performance of the fluid in the boundary layer region. VGs are small vanes not aligned with the incoming flow and located neighboring the leading edge. They act by exchanging momentum from the distant flow region to the wall-closed inner region. Researchers have applied these devices in certain aerodynamics applications in the past fifty years.

The customary VG height is usually similar to the local boundary layer thickness with a 1:2 height to length ratio. These devices modify the flow streamline direction creating flow vorticity. Thus, they generate downstream co-rotating or counterrotating vortices depending on their geometrical configuration.

The installation of these vortex generators mounted on the suction side of aircraft wings or wind turbine blades may be considered a first approach to try to regulate the flow separation because they are easy to design and set-up as well as inexpensive. They can be quite easily assembled as a postproduction fix to the wing or blade when the latter does not work as efficiently as expected. They are also replaceable by a simple and fast procedure and because of their small size a relatively big number of them are able to be spanwise distributed.

VGs generate a small parasitic drag and they need a detailed understanding to be applied correctly and optimized for every flow and geometry. In the work carried by Gao et al. [1] on a 30% thick DU97-W-300 airfoil, the maximum lift coefficient was substantially increased with the insertion of passive VGs. This effect is the result from the delay or prevention of the boundary layer detachment; however, this good performance was counterbalanced by the appearance of a considerable parasitic drag.

In the past years, some models focusing on the vortices produced by vanes have been implemented. For instance, Smith [2] proposed a theoretical model as well as Velte et al. [3] who showed the helical symmetry of vortices produced by a passive four-sided vane-type vortex generator. Additionally, there are VG models using the BAY-model [4] which have been implemented into codes as the Actuator VG model (AcVG) developed in Ref. [5]. These authors introduced body forces by means of source expressions in the energy and momentum equations to reproduce the existence of a passive flow control device.

Triangular and rectangular conventional VGs have been implemented onto wings of airplanes for flow control to efficiently improve mixing of the boundary layer and transfer momentum nearby the wall by delaying or suppressing the flow detachment [6]. Furthermore, in the experimental work performed by Velte [7] and the associated simulations carried out by Fernandez-Gamiz et al. [8] demonstrated that the primary vortex produced by a rectangular VG inserted on a flat plate exhibited self-similarity for axial and azimuthal velocities. In most applications, these VG devices are designed with their height h similar to the local boundary layer thickness d and inserted perpendicular to the surface with an incident angle to the flow to produce streamwise vortices. However, the remaining drag related to these d-scale VG devices might be relatively large in some flow-control application.

The generation of streamwise vortices by means of the insertion of vane-type devices with reduced height is an easy method to enhance their efficiency. Lin et al. [9] proved that when decreasing the height of standard VGs to a value lower than the local boundary layer thickness, the momentum transfer keeps being large enough to avoid or delay flow separation downstream of the VGs. These so-called low-profile VGs were mounted on multi-element high-lift airfoils with the aim of controlling the flow detachment on the flap. Yao et al. [10] compared the deviation in the vortex path between a low-profile VG with height h around 20% the boundary layer thickness d and a standard VG with height h around 20% the boundary layer thickness d and a conventional VG with $h=\delta$.

Ashill et al. [11] in a conceptual and experimental study showed a successful delay of the shock-induced separation on a transonic profile by mounting Sub Boundary Layer Vortex Generators (SBVG). Those wedge SBVGs proved to produce meaningful rises in lift and diminutions in drag. According to [12], the implementation of these low-profile VG devices could be considered as a quite good option to be implemented when the flow-separation positions are relatively fixed and the vanes can be implemented upstream relatively nearly the flow separation.

## 2. Computational Method

### 2.1. Governing Equations

In this study, numerical simulations were performed to solve the incompressible Reynolds-Averaged Navier-Stokes (RANS) equations employing the SST k-ω turbulence model. The SST k-ω model was developed by Menter [13], the model integrates the precise formulation of the k-ω model near the wall region. Steady state computations have been successfully applied to a single VG case placed on a flat plate at two different angles of attack with respect to the oncoming flow [14].

The continuity equation is expressed as:

$$\frac{\partial(\rho\bar{u}_i)}{\partial x_i} = 0 \quad \dots\dots\dots\dots (1)$$

The Navier-Stokes Momentum Equations are given by:

$$\frac{\partial(\rho\overline{u_i u_j})}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_1} + \frac{\partial}{\partial x_J}\left((\mu + \mu_t)\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right) \quad (2)$$

Where, u represents the velocity vector, P is the pressure, ρ is the density, $\mu$ is the molecular viscosity, and $\mu_t$ is the turbulent viscosity.

The SST k-ω Turbulence Model Equations are defined as:

$$\frac{\partial k}{\partial t} + (V \cdot \nabla)k = \nabla \cdot \left[\left(v + \frac{v_t}{\sigma_k}\right)\nabla k\right] + P_k - \beta^* p\omega k \quad (3)$$

$$\frac{\partial \omega}{\partial t} + (V \cdot \nabla)\omega = \nabla \cdot \left[\left(v + \frac{v_t}{\sigma_\omega}\right)\nabla \omega\right] + \frac{\alpha\beta^* p\omega^2}{k} - \beta p\omega^2 \quad (4)$$

Here, k is the turbulent kinetic energy, ω is the specific rate of dissipation, $P_k$ is the turbulent kinetic energy production, and $\sigma_k$, $\sigma_\omega$, α, $\beta$, $\beta^*$ are model-specific coefficients.

### 2.2. Computational Model

The aim of the present computational model is to enhance the aerodynamic performance of a rectangular wing through the strategic application of vortex generators. The specific geometry under examination in this study is a rectangular planform, as outlined by Torres and Mueller, with an Aspect Ratio (AR) of 2. The selection of an AR of 2 is motivated by its demonstrated higher aerodynamic efficiency, particularly suitable for Micro Air Vehicles (MAVs).

This model features flat side edges and elliptical leading and trailing edges with a ratio of 5-to-1, thickness-to-chord-ratio of 2.60% based on the root-chord length. Notably, the parameter Δy, governing the leading-edge shape, is set at 0.74% of the root chord. In the realm of wings operating at Low Reynolds Numbers, the configuration of the leading edge holds paramount importance. Even slight modifications to its shape can exert significant influences on aerodynamic forces, especially the moment coefficient.

For clarity and reference, **Error! Reference source not found.** provides a comprehensive overview of the specifications and geometry parameters pertinent to the wing employed in this investigation. It's noteworthy that xc/4 represents the distance from the leading edge of the root chord to the 25% point of the mean aerodynamic chord (MAC). Additionally, the wing model is characterized by 0% camber, essentially comprising flat-plate airfoils. This deliberate choice of zero camber serves as a benchmark to establish the performance baseline for Low Aspect Ratio (LAR) wings at Low Reynolds numbers. Consequently, any observed enhancements in the performance of cambered wings are interpreted as incremental effects, added to the foundational data derived from flat-plate wings.

**Table 1** Wing Specifications

| AR | Corot, in | Span, in | Area, in$^2$ | $\bar{c}$, in | $x_{\bar{c}/4}$, in |
|---|---|---|---|---|---|
| 2.00 | 6.000 | 12.000 | 72.000 | 6.000 | 1.500 |

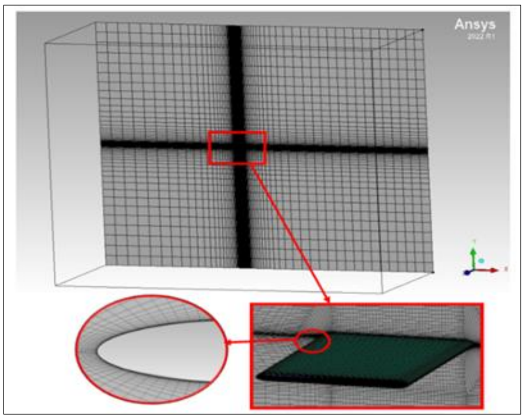



**Figure 1** Computational Model

The grid independent test findings indicate that optimal grid resolution is attained when employing approximately 1.6 million elements, as visually represented in **Error! Reference source not found.**. This refined grid configuration ensures accurate and reliable computational results.

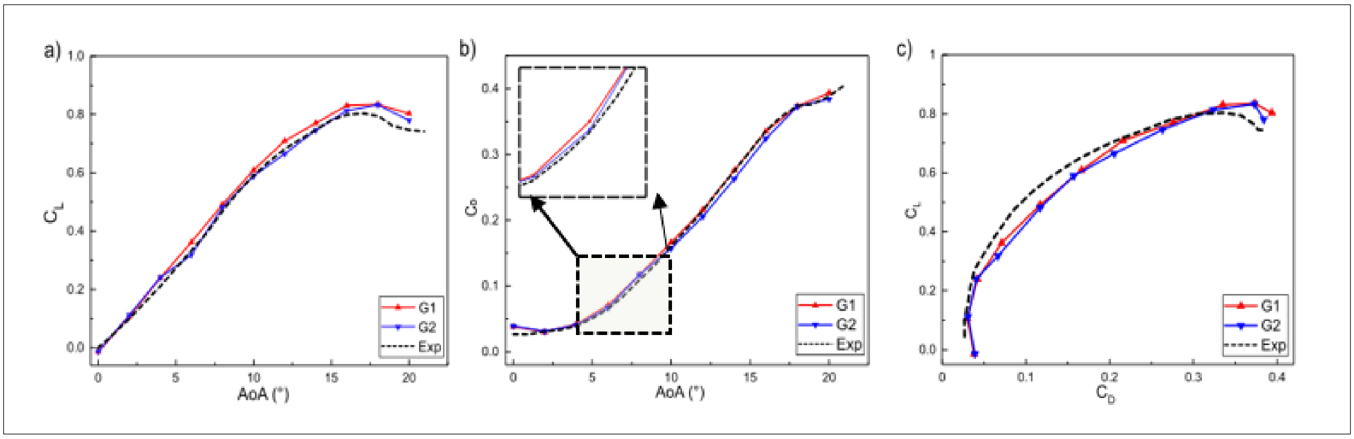



**Figure 2** Comparison of a) Lift Coefficient; b) Drag Coefficient; and c) Lift-to-Drag Ratio of rectangular wing between CFD and Experimental Results

At the inlet boundary, a velocity magnitude of 9.58 m/s is prescribed, corresponding to a Reynolds number (Re) of 100,000 at the chord length, a commonly encountered operational Re value for Micro Air Vehicles (MAVs). Meanwhile, a zero-pressure boundary condition is imposed at the outlet, facilitating realistic simulation of airflow behavior.

In the context of validating the computational model, the angle of attack (AOA) is systematically varied within the range of 0 to 20°. This range captures a spectrum of flight conditions, enabling thorough assessment and validation of the model's predictive capabilities.

To ensure symmetry and realism in the simulation, symmetrical wall boundary conditions are applied, mirroring the physical properties and behavior of the actual aerodynamic surfaces. These boundary conditions play a crucial role in accurately capturing the flow physics, especially in scenarios where symmetry or boundary effects are significant.

### 2.3. Validation of Numerical Model

The objective of this validation process is twofold: to validate the accuracy of the pre-processing setup and to verify the appropriateness of the selected boundary conditions. This validation is crucial for establishing confidence in the computational method's reliability. To achieve this, a comprehensive comparison is made between the numerical results obtained from Ansys Fluent simulations and the meticulously gathered experimental data by Mueller and Torres.

A meticulous comparative analysis is conducted to assess the performance of both the lift and drag coefficients as predicted by the numerical simulations in comparison to the experimental data. **Error! Reference source not found.**

illustrates the results of this comparison. Remarkably, **Error! Reference source not found.** (a) demonstrates that most lift coefficient values across the entire angle of attack (AOA) range from 0° to 20° fall within a specified 10% margin of error when compared to the experimental data. This indicates a high level of agreement between the numerical predictions and the experimental observations. Furthermore, the numerical model accurately predicts the stall angle for this low aspect ratio wing, with both sets of results indicating a stall delay occurring at relative angles between 18° to 20°. Notably, both the simulations and the experimental data exhibit very low lift slopes, a characteristic commonly associated with low aspect ratio wings.

Similarly, the drag coefficient values obtained from the simulations closely match the experimental data, particularly within the pre-stall angle ranges. These findings collectively provide compelling evidence of the computational model's efficacy in accurately predicting both lift and drag coefficients for the rectangular wing under investigation. should be centered in the column and numbered sequentially.

Given the strong correlation between the numerical predictions and experimental data across various aerodynamic parameters, it is reasonable to conclude that the computational framework employed in this study has demonstrated superior performance and reliability. Therefore, it can be confidently asserted that the numerical model is sufficiently verified for application in future endeavors related to similar aerodynamic analyses. This validation not only enhances confidence in the current study's findings but also lays a robust foundation for further advancements in the field of computational aerodynamics.

**Table 2** Grid Sensitivity Study

| Case | Method | Grid Size | α (°) | $C_L$ | $C_D$ |
|---|---|---|---|---|---|
| G1 | Menter's transition SST model | 125x95x60 | 0 | -0.01303 | 0.039009 |
| | | | 4 | 0.241375 | 0.040726 |
| G2 | Menter's transition SST model | 162x135x75 | 0 | -0.01366 | 0.038047 |
| | | | 4 | 0.23963 | 0.041979 |
| Wind Tunnel | | | 0 | -0.000923 ± -0.0126 | 0.0265±0.03408 |
| | | | 4 | 0.2119 ± 0.25209 | 0.03876±0.04215 |

## 3. Response Surface Method

Response Surface Method (RSM) is widely recognized and frequently used surrogate modeling technique designed to approximate computationally intensive simulation codes usually with low-order polynomials. The basic RSM process involves several critical steps. Initially, a set of design points is carefully chosen. These points are specific combinations of input variables where the computationally expensive function will be evaluated. This step is fundamental as it forms the basis for constructing an accurate and reliable surrogate model. After the function has been evaluated at these design points, the data collected is utilized to construct response surfaces. These surfaces act as approximations that represent the functional relationships between the design variables and the objective functions. A regular optimization procedure is then applied on the response surfaces to find optimal solutions.

The response surface approximation is commonly selected to be a low-order polynomial due to its simplicity and effectiveness. The second-order model is widely used because of its flexibility and ease of use. A second-order response surface model with d variables can be written as the following:

$$y = \beta_0 + \sum_{i=1}^{d} \beta_i x_i + \sum_{i=1}^{d} \beta_{ii} x_i^2 + \sum_{j=2}^{d} \sum_{i=1}^{j-1} \beta_{ij} x_i x_j + \varepsilon \quad (5)$$

Where xi are the predictor variables, β are the ρ regression coefficients, and ε denotes the total error, which is the difference between the observed and the estimated response value. The unknown regression coefficients are typically estimated using the method of least squares. The fitting model written in matrix form is

$$\hat{y} = Xb \qquad (6)$$

Where ŷ = [ŷ1, ŷ2, …, ŷn] T is the estimated response vector of the n observed response vector ŷ= [y1, y2, …, yn], X is the matrix of model terms evaluated at the design points. b is the least-squares estimator of regression vector β, which is estimated to minimized the sum of the squares of the error SSE defined as follows:

$$SS_E = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (7)$$

In the context of aerodynamic optimization, RSM proves to be an indispensable tool. It allows for the development of mathematical models that effectively capture the relationships between input variables (such as design parameters) and output responses (such as lift and drag coefficients). This capability is particularly beneficial when exploring complex systems, as it significantly reduces the need for extensive computational resources.

In our study, we used RSM to refine the computational model and improve its predictive accuracy, focusing on the aerodynamic behavior of a rectangular wing equipped with VGs. The goal was to optimize the design and placement of these VGs, which are crucial for enhancing the aerodynamic performance of MAVs. By employing Design Expert Software, we systematically explored various VG design variables, such as the number of VG pairs, their spacing, and their geometric characteristics, to identify the optimal configuration for improving MAV performance. The advanced features of the software enabled precise point predictions and design optimizations, allowing us to streamline the exploration process and maximize performance efficiency, as shown in

Table 3.

The key VG parameters included the height (h), length (L), and the spacing between VG pairs (d), as well as critical angles such as the inclination angle (γ) and skew angle (β). These VGs were designed as rectangular trapezoids and positioned normal to the wing surface, with the leading edges carefully aligned along the wing's abscissa (xd). Additionally, the distance between the trailing edges of the VGs and the measurement station (ΔXVG) was included in the analysis, as it plays a significant role in determining the aerodynamic effects generated by the VGs. Figure 3 provides a detailed visualization of these VG characteristics.

By integrating RSM with advanced software like Design Expert, we were able to utilize low-order polynomial approximations that strike a balance between computational simplicity and capturing key system behaviors. This approach is particularly advantageous in the context of MAVs, where computational resources are often limited, and aerodynamic performance is critical. Our study highlights the importance of carefully optimizing VG design, providing a foundation for future advancements in MAV technology and aerodynamic research.

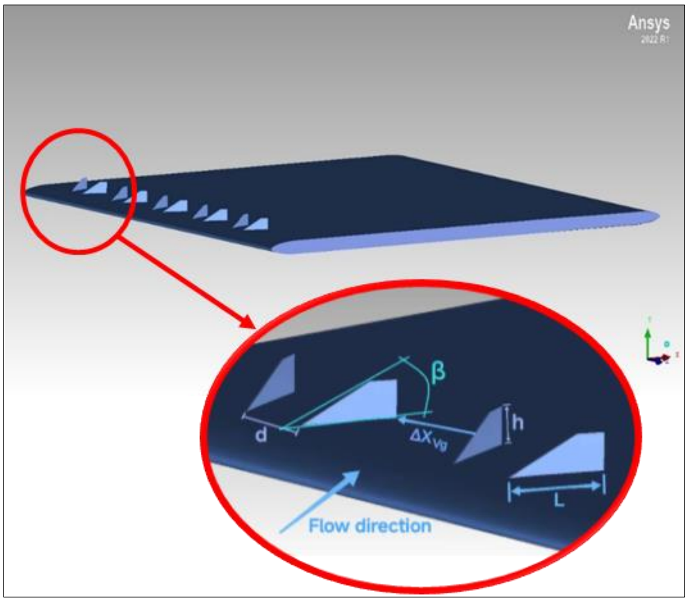



**Figure 3** Geometry of VGs

**Table 3** Range of Values of Vg Parameters

| h/δ | L/h | d/h | β rad | γ rad |
|---|---|---|---|---|
| 0.2-0.4 | 1-5.6 | 0.5–6.6 | 0.26-0.5 | 1.22 – 2.44 |

## 4. Results

The VG parameters, including h, L, d, and critical angles such as γ and β, play a crucial role in optimizing aerodynamic performance by controlling airflow and influencing the boundary layer. The height of a VG is particularly important, as it determines how deeply the VG interacts with the boundary layer. A taller VG can generate stronger vortices, which help energize the boundary layer and delay flow separation. However, if the height is too great, it can also cause excessive drag, diminishing the performance gains. Achieving the optimal height is key to enhancing lift without introducing unwanted drag. Research has shown that increasing VG height up to a certain threshold increases boundary layer mixing, but beyond that threshold, drag begins to outweigh the benefits in lift improvement [14]. As we can see in Figure 4, the relationship between VG height and drag shows a steep rise as height exceeds this optimal point.

The length of the VG is another important factor, as it affects the size and persistence of the vortices. A longer VG typically creates more powerful vortices, helping the airflow remain attached to the surface for a longer distance, which is especially useful in preventing flow separation on wings or similar surfaces. However, a longer VG also increases surface area and can lead to higher skin friction drag, so the length must be carefully balanced to achieve the desired effect. Studies on VG length indicate that while longer vortex generators improve boundary layer attachment, they also increase frictional drag by 5–10% compared to shorter VGs [15]. This is evident in Figure 4, where the drag coefficient rises with increasing VG length.

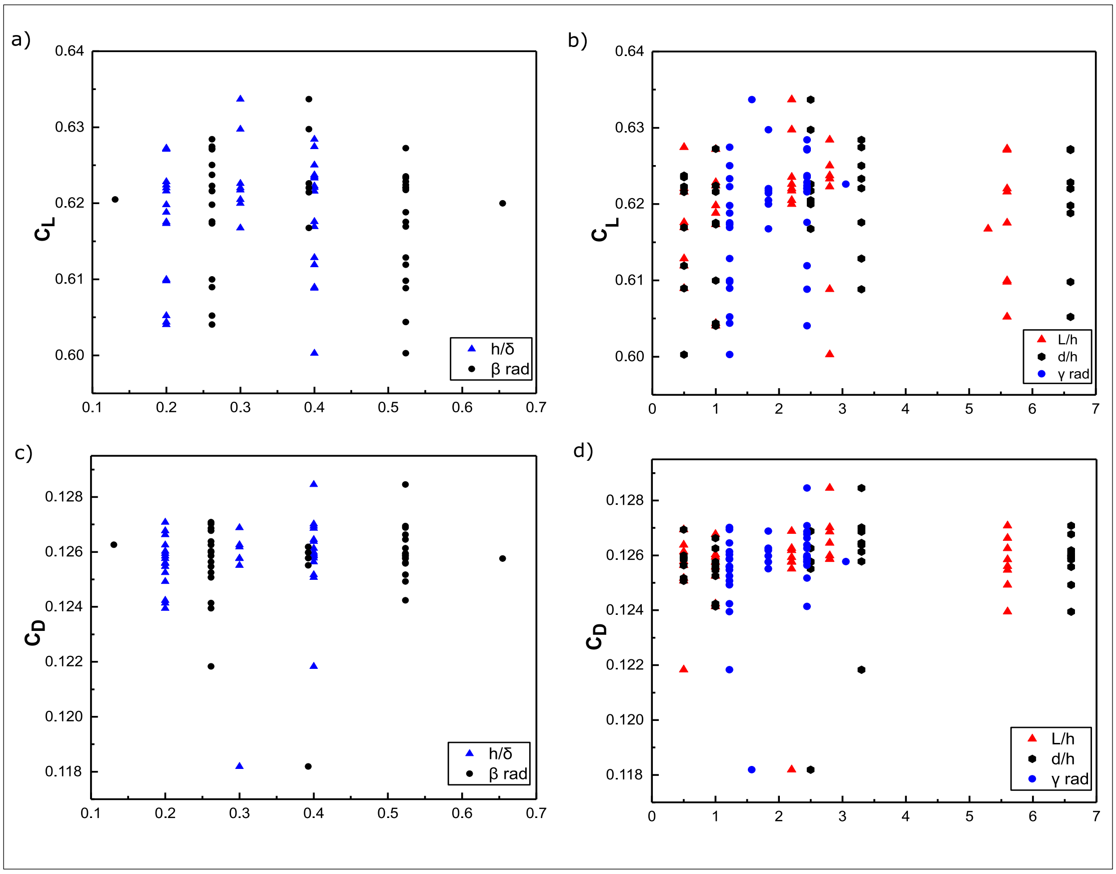



**Figure 4** Lift and Drag distribution for different parameters of VGs at 10° AoA

Spacing between VG pairs also plays a significant role in determining the effectiveness of the vortices. If the spacing is too narrow, the vortices may interact and lose their individual effectiveness, while spacing them too far apart can leave gaps where the boundary layer may not be properly energized. Proper spacing allows for effective interaction of vortices, leading to better control over the flow and improved overall performance. Experimental findings suggest that optimal spacing is typically around 5-10 times the VG height, minimizing vortex interference and maximizing boundary layer energy [16]. This trend is clearly shown in Figure 4, where performance metrics plateau around the optimal spacing.

The inclination angle (γ), influences the angle at which the vortices are generated. A higher inclination angle, generally results in stronger vortices, which can more effectively re-energize the boundary layer and delay separation. However, increasing this angle too much can lead to increased drag, as the VG becomes more exposed to the oncoming airflow. Therefore, optimizing the inclination angle is crucial for achieving strong vortex generation without negatively impacting aerodynamic efficiency. In Figure 4, we can observe how inclination angle impacts both lift and drag coefficients, with the optimal range providing the best balance. The skew angle (β), which defines the orientation of the VG relative to the airflow, introduces a lateral component to the vortex generation. This lateral effect helps control the flow over a wider area and can be useful for managing crossflow instabilities. A skew angle in the range of 0.35–0.52 radians is often considered optimal. By choosing the correct skew angle, it is possible to ensure that the boundary layer remains attached over a larger surface area. However, as with the inclination angle, if the skew angle is too large, it can lead to higher drag. Studies have shown that a skew angle between 0.35 and 0.52 radians is effective in controlling crossflow while maintaining minimal drag penalties [17]. As illustrated in Figure 4, the skew angle directlyinfluences the flow behavior, affecting both lift and drag based on the chosen angle.

The integration of computational fluid dynamics (CFD) and Response Surface Methodology (RSM) in the aerodynamic optimization of Micro Aerial Vehicles (MAVs) has revealed an important and innovative finding: vortex generators (VGs), while traditionally employed to improve lift, are far more effective in reducing drag in MAV applications. This is particularly significant for MAVs, where low drag is essential for enhancing flight efficiency and endurance. Our analysis at a 10° angle of attack (AoA) showed that VGs had a modest impact on lift, increasing the lift coefficient by only 2%, from 0.591624 to 0.633685. However, the drag reduction achieved by VGs was substantial, with the drag coefficient decreasing by nearly 26%, from 0.160094 to 0.11819. This indicates that VGs are crucial for minimizing drag and improving overall aerodynamic performance.

The optimal configuration: $h/\delta=0.3$, $L/h=2.2$, $d/h=2.5$, $\beta=0.39$ radians, and $\gamma=1.57$ radians, at a 10° AoA produced a lift-to-drag ratio of 5.10775, demonstrating that careful tuning of these parameters can significantly reduce drag while maintaining a satisfactory level of lift. This configuration successfully balanced vortex generation and flow control, which contributed to enhanced aerodynamic efficiency.

In Figure 5, we can observe a comparison of the lift coefficient between the rectangular wing, with and without VGs, at 6° AoA without VGs reflects an improvement of approximately 3.23%. This demonstrates how the vortex generators enhance lift by energizing the boundary layer and delaying flow separation, even at moderate angles of attack. By keeping the flow attached to the wing surface for longer, the VGs allow the wing to generate more lift. However, the increase in lift at this angle is relatively moderate and could be considered insignificant in the broader context of performance improvements. At 10° AoA, the lift coefficient rises from 0.591624 without VGs to 0.633685 with VGs, resulting in a 7.10% lift enhancement. Here, the VGs start to show their value by mitigating flow separation, which becomes more pronounced in the baseline wing without VGs. At 16° AoA, where flow separation is more severe without VGs, the lift coefficient increases from 5.81% improvement. Despite the relatively small increase, the VGs help maintain higher lift at this high angle of attack by continuing to delay separation.

In Figure 6, the drag coefficient reveals the benefits of the optimized VG configuration in reducing resistance. At 6° AoA, the drag coefficient results in a 20.31% reduction. This shows that even at moderate angles of attack, VGs can reduce drag by streamlining the airflow. At 10° AoA, the drag reduction becomes more substantial, with the coefficient decreasing 26.18%. This highlights the ability of VGs to improve aerodynamic efficiency by managing boundary layer separation. At 16° AoA, the drag coefficient drops to 24.53% reduction. Despite the challenging conditions at this high angle of attack, the VGs significantly reduce drag, making the wing more aerodynamically efficient.

The reduced drag seen in this study aligns with findings of [11] who noted that VGs, particularly low-profile ones, have a much more pronounced effect on reducing drag than enhancing lift, especially in subsonic flows. Similarly, [10] demonstrated that drag reduction via VG implementation is a critical factor in improving aerodynamic performance in aircraft, and our results confirm that this applies equally to MAVs. The reduced drag achieved through VG optimization directly translates to better flight efficiency and endurance, key performance metrics for MAVs that operate with limited power supplies and are often designed for extended flight durations.

Overall, the study demonstrates that there is an insignificant lift enhancement in some regions, particularly at 6° AoA, the VGs provide clear aerodynamic benefits in other areas. This confirms that the optimized VG configuration enhances overall performance, offering significant drag reduction while moderately improving lift, especially in critical flight conditions.

Moreover, the results of this study mark a shift in how VGs are viewed in aerodynamic design. Traditionally, VGs have been implemented primarily to enhance lift by re-energizing the boundary layer and delaying flow separation. However, our findings suggest that, particularly for MAVs, the primary benefit of VGs is their ability to minimize drag, rather than significantly increasing lift. This is an important distinction because MAVs, which often operate at lower Reynolds numbers and are designed for high efficiency over long periods, benefit more from drag reduction than from minor improvements in lift. As [18] similarly observed that while VGs could lead to minor lift improvements, their main advantage in small-scale aerial vehicles lies in controlling drag and improving flow characteristics around the wings.

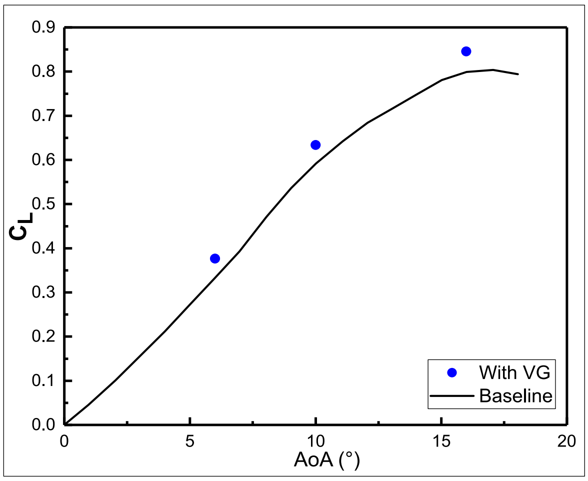



**Figure 5** Comparison of Lift Coefficient between the Rectangular Wing with and without VGs

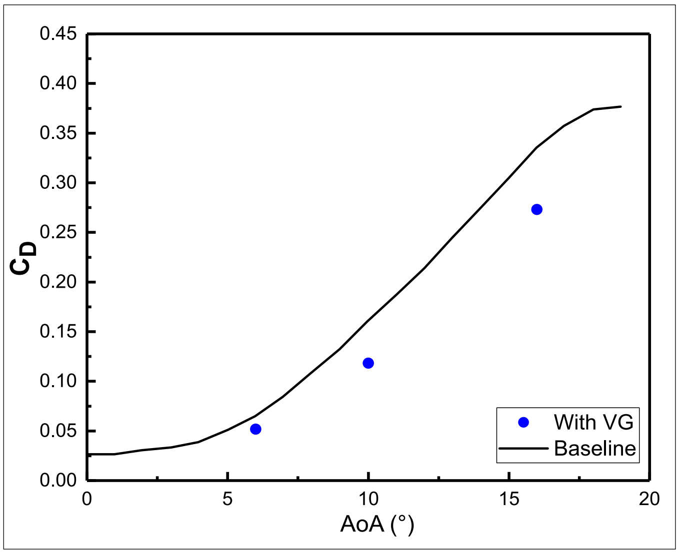


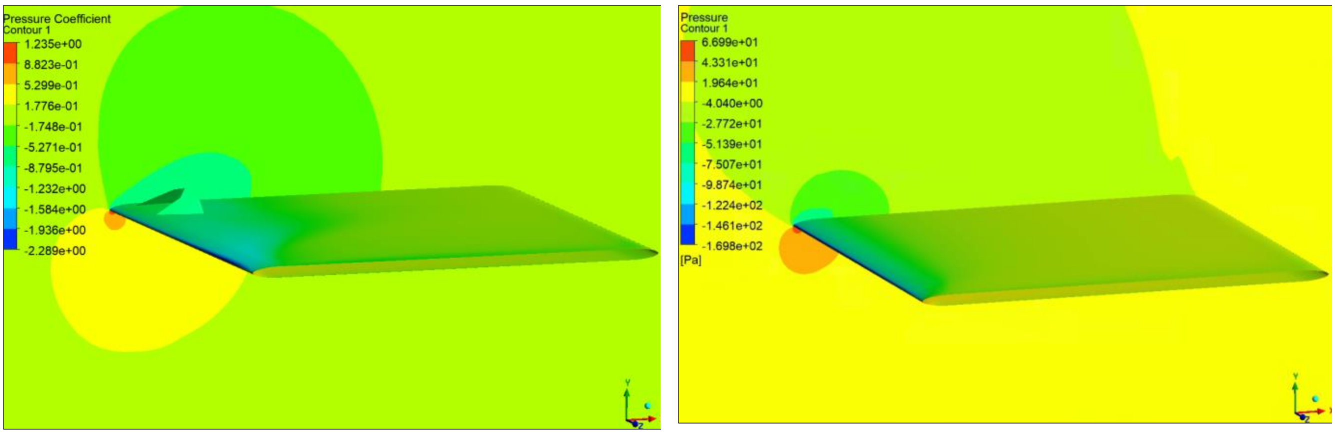

**Figure 6** Comparison of Drag Coefficient between the Rectangular Wing with and without VGs

In Figure 7 we can observe a comparison between the pressure and velocity contours of a wing with and without VGs at a 10° AoA demonstrates the significant aerodynamic improvements VGs provide. As we can see in Fig. 7 a), the pressure contour for the wing with VGs shows a more uniform pressure distribution across the surface, especially near the leading edge. This is consistent with the work of Lin [11], who explained that VGs energize the boundary layer, allowing the flow to remain attached for longer, thus improving aerodynamic performance by reducing pressure drag. In contrast, Fig. 7b), which represents the pressure contour without VGs, shows higher pressure variations, indicating earlier flow separation and a reduction in lift efficiency. This observation aligns with findings by Godard and Stanislas

[19], who noted that wings without VGs suffer from premature flow separation at high angles of attack, which increases drag and reduces lift.

In terms of the velocity distribution, as seen in Fig. 8 a), the presence of VGs results in higher flow velocities near the wing's surface, particularly in areas prone to flow separation at higher AoA. This agrees with Pearcey's research [20], which highlights how VGs can sustain higher velocity gradients along the surface by delaying boundary layer separation. On the other hand, Fig. 8 b), which shows the velocity contour without VGs, reveals a significant deceleration in airflow toward the trailing edge, suggesting early separation. This pattern corresponds to Schubauer and Spangenberg's work [5], which demonstrated the adverse effects of early boundary layer separation on aerodynamic performance, leading to higher drag and reduced lift.

The overall effect of VGs on the wing's performance is clear from these comparisons. VGs create small vortices that mix high-energy air into the boundary layer, helping to maintain the attachment of airflow and thereby preventing early flow separation. This leads to a significant improvement in aerodynamic efficiency, particularly at higher AOAs. Rao et al. [21] observed a similar effect, where VGs reduced drag by re-energizing the boundary layer and maintaining airflow attachment over a larger portion of the wing. Furthermore, Tanguy and Garnier [6] showed that the use of VGs resulted in better lift-to-drag ratios, particularly in high AOA scenarios, which is evident in the enhanced performance of the wing with VGs, as seen in the pressure and velocity contours.

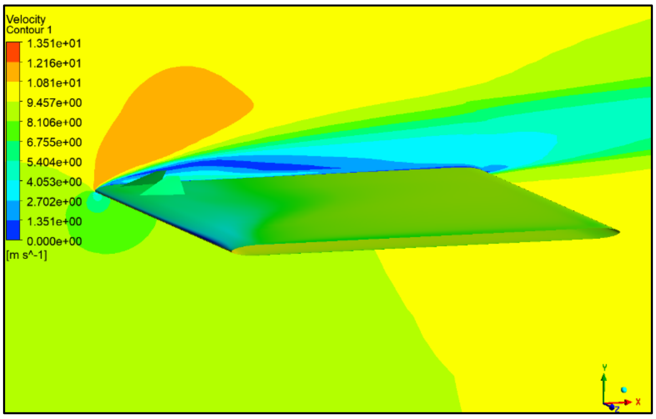



Pressure Coefficient Contour with VGs at 10° AoA

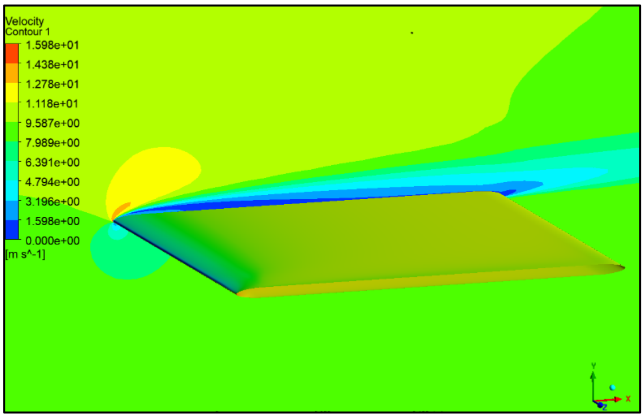
Pressure Coefficient Contour Without VGs at 10° AoA

**Figure 7** Comparison Between Pressure Contour Between a) Wing with VGs and b) Without VGs

The contour plots demonstrate that VGs significantly improve the aerodynamic performance of a wing by maintaining lift, reducing drag, and preventing flow separation. These results are consistent with previous studies [1-6], reinforcing the importance of VGs in modern aerodynamic design.



Velocity Contour with VGs at 10 Degrees AoA



Velocity Contour Without VGs at 10 Degrees AoA

**Figure 8** Comparison Between Velocity Contour between a) Wing with VGs and b) Without VGs

## 5. Conclusion

This study explored the effects of low-profile VGs on the aerodynamic performance of MAVs, particularly focusing on a rectangular wing configuration. Using computational simulations, we investigated how VGs influenced key parameters such as lift, drag, and boundary layer behavior at a Reynolds number of 100,000. The RSM was employed to optimize the configuration of the VGs, leading to significant improvements in performance.

One of the most important findings is the substantial drag reduction achieved by the optimized VG configuration. At a 10° AoA, the drag coefficient was reduced by 26%, showing that VGs can dramatically improve flight efficiency by controlling boundary layer separation. This is critical for MAVs, where reducing drag enhances endurance and maneuverability. MAVs often operate in low-Reynolds-number regimes, which makes them particularly susceptible to early flow separation and drag increase. The inclusion of VGs mitigated these effects, resulting in smoother airflow and less aerodynamic resistance, thus improving overall flight performance.

The study also highlighted the effect of VGs on lift. While the increase in lift was modest compared to the drag reduction, it was still noteworthy. At 10° AoA, the lift coefficient saw a 7% improvement. This suggests that while the primary benefit of VGs in MAV applications is drag reduction, they also contribute to maintaining or slightly improving lift, particularly at higher AoAs where flow separation is more likely to occur. VGs helped re-energize the boundary layer, allowing the wing to maintain attached flow and thus improve its aerodynamic characteristics even at critical angles.

The contour plots of pressure and velocity provided further insights into the mechanisms by which VGs improve aerodynamic performance. The pressure contour for the wing equipped with VGs showed a more uniform distribution across the surface, reducing pressure gradients that contribute to drag. In contrast, the wing without VGs exhibited significant pressure variations, indicating earlier flow separation and less efficient performance. The velocity contours also revealed that the VGs sustained higher surface velocities over the wing, which contributed to delayed flow separation and improved aerodynamic efficiency. These findings suggest that the role of VGs extends beyond just lift enhancement; they are highly effective in controlling flow behavior, reducing drag, and improving overall stability.

By employing RSM, we were able to optimize the VG configuration to achieve the best balance between lift and drag. The optimal configuration included careful adjustments to VG height, length, spacing, inclination, and skew angles. This allowed us to fine-tune the VG design to maximize aerodynamic performance for MAV applications. The result was a configuration that minimized drag without sacrificing lift, providing a more efficient and stable flight profile.

In conclusion, this research confirms the significant benefits of low-profile VGs in improving the aerodynamic performance of MAVs. The primary advantage lies in their ability to reduce drag and maintain efficient flight characteristics, particularly at higher angles of attack where flow separation is a major concern. Although the lift improvements were modest, the overall aerodynamic enhancements provided by VGs especially in drag reduction make them an essential tool in MAV design. The successful application of RSM in optimizing VG configuration also demonstrates the potential for further advancements in aerodynamic optimization for small aerial vehicles. The findings from this study provide a foundation for future research and practical applications in MAV development, especially in fields where efficiency and extended flight endurance are critical.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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