11th European Conference for AeroSpace Sciences (EUCASS) - 30th June to 4th July 2025

DOI: ADD DOINUMBER HERE

Computational Investigation of Twist Morphing Rotor Blades for Aerodynamic Efficiency Enhancement

Mars Burke† and Alvin Gatto**

** Mechanical and Aerospace department, Brunel University of London*

Kingston Ln, Uxbridge, London, UB8 3PH, UK

Mars.Burke@Brunel.ac.uk – Alvin.Gatto@Brunel.ac.uk

† Corresponding Author

Abstract

The aerodynamic performance of rotorcraft blades plays a pivotal role in determining rotor system efficiency; directly impacting lift generation, fuel consumption, and mission endurance. Conventional rotor designs, constrained by fixed blade geometries, impose inherent limitations on optimising aerodynamic efficiency across varying flight conditions. This study investigates the feasibility of twist-morphing rotor blades, wherein a full-chord twist technique is introduced to enhance aerodynamic performance. A high-fidelity computational fluid dynamics (CFD) analysis was conducted using high-performance computing (HPC) infrastructure (SimScale) across 10 case studies to evaluate the aerodynamic effects of this morphing technique on a baseline Sea King rotor blade. The analysis investigated a spanwise section of 0.85 r/R (where r/R represents the spanwise blade position normalised by radius), with twist angles varying from -14° to +14°. A RANS steady-state solver (k-omega SST) was employed for cruise and hover conditions, with velocity-pressure coupling. In hover mode, the greatest increase in CL/CD was observed when a linear +10° was applied to the morphing section, improving the aerodynamic efficiency by 6.3%. At cruise conditions, the highest increase in aerodynamic efficiency was observed at +14° where the CL/CD improved by 31%. The findings validate twist morphing as a viable mechanism for aerodynamic enhancement, demonstrating its potential to improve rotorcraft performance. The insights provide a quantitative foundation for integrating morphing rotor technology into the next generation of rotorcraft engineering. While the aerodynamic benefits are evident, future research must address aeroelastic modelling, structural dynamics, and real-time actuation feasibility to ensure practical implementation in the future rotary-wing aircraft.

1. Introduction

Rotorcraft modelling has, for many decades, garnered significant attention across various engineering domains, notably in the design and analysis of wind turbines, ducted fans, and helicopter rotor systems. The complexity of these systems arises from their inherently unsteady and three-dimensional aerodynamic environments, posing challenges for performance optimisation. While recent advances have led to substantial progress in structural vibration control and noise mitigation, the aerodynamic aspects of rotorcraft (particularly in relation to efficiency and performance) have not been the subject of commensurate scrutiny. This relative underrepresentation is critical, as aerodynamic performance directly influences essential parameters such as power consumption, range and overall mission endurance. Traditional rotor blade designs, characterised by fixed geometries, are optimised for a narrow set of operating conditions. As a result, they exhibit inherent inefficiencies when subjected to off-design states, such as changes in flight speed, altitude, or manoeuvring conditions. To address these limitations, this study explores the aerodynamic potential of twist morphing rotor blades; a form of adaptive structure capable of dynamically altering blade twist in response to changing aerodynamic loads. Morphing technology introduces an additional degree of freedom into the blade design space, allowing for localised optimisation of aerodynamic forces. Of particular interest in this investigation is the impact of twist morphing on the aerodynamic envelope, specifically the lift-to-drag ratio (CL/CD), which serves as a proxy for overall aerodynamic efficiency. In contrast to previous studies, which have mainly highlighted the structural feasibility or noise and vibration reduction of rotor blades, this work focuses on determining the aerodynamic benefits achieved by linear spanwise twist employed across the entire blade's chord. Numerous computational fluid dynamics (CFD) studies have previously explored a range of morphing strategies and mechanisms, including trailing-edge flaps [1–3], active camber and active twist [3], partial-chord morphing concepts [4], and nose droop configurations [5]. However, to date, none have implemented or systematically evaluated a full-chord active twist mechanism for rotor blades.

A comprehensive computational investigation by Woodgate et al. [1] into the aerodynamic effects of Gurney flaps on both fixed-wing and rotor blade configurations revealed that, in comparison to fixed-geometry blades, the modelling of Gurney flaps on rotor systems presents significantly greater complexity. The increased intricacy stems not only from the unsteady nature of rotor aerodynamics but also from the challenges associated with accurately capturing the flow interactions and structural responses introduced by flap integration. The study employed high-fidelity CFD simulations to optimise critical parameters of the Gurney flap—namely its size, chordwise location, and spanwise extent. Results indicated that the inclusion of a Gurney flap yielded a notable increase in rotor thrust, approximately 7.4%. However, this gain came at the cost of an undesirable aerodynamic side effect: a mean nose-down pitching moment increase of around 20% across the azimuthal range. This necessitated a rigorous evaluation of flap geometry to mitigate its destabilising influence on blade pitch control and overall rotorcraft handling. To support the analysis, a variable boundary condition method was employed within the CFD framework, enabling dynamic flap adjustment without mesh deformation. Gurney flaps were modelled as thin, embedded surfaces actuated through boundary condition control. The study confirmed that while Gurney flaps can enhance lift and thrust, they also introduce notable drag and increased pitching moments, highlighting the need for careful aerodynamic optimisation when integrating such devices into rotorcraft systems.

Gagliardi and Barakos [2] conducted a detailed investigation into the application of deployable trailing-edge flaps to enhance the hover performance of low-twist helicopter rotors. Their objective was to retain the forward-flight efficiency associated with low-twist blades while achieving hover performance comparable to highly twisted configurations. Employing both blade element theory and high-fidelity Reynolds-Averaged Navier–Stokes (RANS) CFD simulations, the study examined a range of fixed flap configurations, with parametric variations in spanwise position, chord length, deflection angle, and flap span. The optimal configuration identified was an inboard slotted flap positioned at approximately 24% span, with 32% chord and 10° deflection, located at around 48% of the blade radius. This design yielded an improvement in the figure of merit of up to 4.7%, comparable to the performance of a blade with an additional 6° of twist. Conversely, outboard flap configurations were found to have limited or adverse effects under high-thrust conditions. A blended inboard flap design—more representative of feasible implementation—demonstrated up to a 6.5% increase in performance and was shown to match the thrust efficiency of a −10° twisted blade, while also reducing trim angles by up to 1°. The findings underscored the viability of passive flap integration for improving hover performance without degrading forward-flight capabilities. Nonetheless, the study also identified challenges related to increased wake interactions and structural complexity, which warrant further investigation.

Huang et al. in a 2021 investigation [3] explored the effects of dynamically altering the blade planform using active camber and active twist techniques. The study focused on a modified, isolated BO105 rotor and successfully validated the performance of a coupled CFD/CSD framework. In this configuration, the actively controlled section was embedded between 25% and 95% of the blade span, with a smooth linear transition to the passive inboard and outboard regions. The active segment was dynamically morphed from 75% chord to the trailing edge, following a non-harmonic control schedule. This approach enabled comprehensive assessment of the aerodynamic and structural implications of morphing under operationally relevant conditions.

Khoshlahjeh et al. [4] examined the application of a trailing-edge plate (TEP) as a deployable morphing mechanism to mitigate stall and extend the operational envelope of the UH-60A helicopter. The TEP, constituting a 20% chord extension over a 20% spanwise segment of the blade (from 63% to 83% of the radius), was actuated downward by 2° through a motor-driven morphing truss and deployed via an internal blade slit. Aerodynamic data for the modified airfoil, obtained through CFD simulations, were integrated with structural modelling in RCAS to evaluate performance across varying speeds, altitudes, and gross weights. Under stall-prone conditions, the TEP reduced rotor power requirements by up to 18%, while enabling an increase in maximum gross weight by approximately 1500 pounds, operational ceiling by 1800 feet, and cruise speed from 115 to 133 knots. At 115 knots, power consumption was reduced by nearly 12%, and minimum cruise power was lowered by 4.3%. Unlike a fixed chord extension, the TEP offered comparable aerodynamic benefits at high loading and altitude without incurring the 4% power penalty at low weight and sea level, owing to its retractability. Additional advantages included minimal actuation effort, adaptability to varying flight regimes, and improved performance near operational boundaries. However, drawbacks were also identified, such as increased pitch link loading at higher deflection angles, aerodynamic inefficiencies due to elastic twist at the blade tip, and challenges related to structural integration.

Martin et al. [5] investigated a Variable Droop Leading Edge (VDLE) concept for dynamic stall mitigation on the VR-12 airfoil under compressible flow conditions representative of retreating blade stall. The configuration incorporated a 25% chord leading-edge segment, hinged at the quarter-chord and actuated via external linkages, allowing either fixed or variable droop during pitching oscillations. In the variable configuration, the droop section remained stationary in space while the primary airfoil underwent oscillatory motion, thereby modifying the effective leading-edge profile throughout the cycle. Experimental data from wind tunnel testing (Mach numbers ranging from 0.2 to 0.45 and reduced frequencies up to 0.1), supported by CFD simulations, indicated substantial aerodynamic benefits. These included drag reductions of up to 63%, peak pitching moment reductions of 31–37%, and complete elimination of negative pitch damping, with lift penalties constrained to approximately 8%. Compared to the fixed-droop configuration, the VDLE offered superior performance by minimising drag and moment penalties at low angles of attack, reducing zero-angle drag by a factor of three. The concept demonstrated effective stall control across a range of Mach regimes, with relatively low mechanical complexity for two-dimensional implementation. Nonetheless, limitations included moderate lift reduction and the practical challenge of integrating the variable mechanism into full-scale rotor blade architectures. Overall, the findings highlight the VDLE's promise for rotorcraft stall alleviation and improved aeroelastic stability.

Collectively, these computational studies [1-5] demonstrate the significant promise of morphing technologies, ranging from trailing-edge flaps and camber modification to leading-edge droop devices in enhancing specific performance attributes of rotorcraft blades. However, each of these approaches is limited either by partial-span or partial-chord actuation, localised aerodynamic benefit, or structural complexity that impedes full-scale implementation. Most critically, the majority of prior investigations focus on mitigating discrete performance deficits—such as stall, vibration, or trim efficiency rather than offering a holistic enhancement of aerodynamic efficiency across the operational envelope (see Table 1). What remains notably absent in the current body of literature is a comprehensive investigation into full-chord, spanwise-distributed twist morphing as a primary mechanism for aerodynamic optimisation. Unlike trailing-edge or sectional modifications, twist morphing has the potential to globally influence blade aerodynamics in a continuous and controllable manner, offering a scalable solution to off-design inefficiencies without introducing significant drag or structural discontinuities. Accordingly, this study aims to bridge this research gap by evaluating the aerodynamic benefits of full-chord, linear spanwise twist morphing using high-fidelity CFD analysis. The objective is to quantify its influence on the lift-to-drag ratio (CL/CD), with a focus on identifying performance gains across a range of twist angles and flight conditions. By establishing a clearer understanding of how twist morphing reshapes the aerodynamic envelope, this work contributes to the foundational knowledge required for the next generation of efficient, adaptable rotorcraft designs.

Table 1: Rotary morphing computational investigations

Author & year	**Purpose of CFD**	**Vibration reduction**	**Noise reduction**	**Performance**
Taylor (1980)	Vibration reduction	↓85%	●	●
Shaw (1980)	Vibration reduction	↓86%	●	●
			●	●
Du Val (1981)	Vibration reduction	↓96%	●	●
Hammond et al. (1981)	Vibration reduction	↓62%	●	●
Davis (1984)	Vibration reduction	↓85%	●	●
Du Val (1987)	Vibration reduction	↓96%	●	●
Kim et al. (2007)	Vibration reduction	●	●	actuation auth. ↑ 2.1-3.5X
Kota et al. (2008)	Performance	●	●	↑35% in CL_{Max}
Gagliardi et al. (2009)	Performance	↑37.3% to 126%	●	↑2.4% FOM
Kammegne et al. (2015)	Performance	●	●	↓3–10.5% drag
Takeda et al. (2015)	Performance	●	●	↑+1.5% FOM
Chia et al. (2017)	Noise & vibration reduction	↑47.1% near-field ↑14% far-field.	↓in-plane noise 6 dB	out-of-plane noise ↑ (up to 18 dB)
NASA RVLT Program (2014–2020)	Noise reduction	Some studies include it	↓up to 15 dB (blade redesigns, modulations)	Trade-offs studied: performance retained or improved
Xiong et al. (2020)	Noise reduction	●	KDE: ↓2.1 dB (hover), ↓1.1 dB (forward flight) APC: ↓4.0 dB (hover), ↓1.3 dB (forward flight), ↓ 6dB (experiment)	Thrust ↑ up to 5.1% (KDE), ↑3.9% (APC)
Thurman et al. (2024)	Noise reduction & performance	●	↓ up to 4 dB SEL reduction during BVI descent	Performance maintained in hover; minor impact in forward flight

2. Methodology

This study utilises SimScale, a cloud-based computational engineering platform, to conduct high-fidelity simulations of twist-morphing rotor blades [6]. SimScale provides access to advanced finite volume solvers, scalable high-performance computing (HPC) resources, and a fully integrated online interface for setting up, running, and analysing computational fluid dynamics (CFD) cases. Its architecture allows efficient simulation management and parallel processing, making it particularly suitable for iterative parametric studies such as the one under investigation in this paper. The objective of this investigation is to evaluate the aerodynamic effects of partial-span twist morphing, applied linearly across the full chord, on a baseline Sea King rotor blade. This morphing concept involves introducing controlled angular deformation (twist) along a defined spanwise section to enhance aerodynamic efficiency. A total of 10 CFD simulations were conducted (7 at hover and 3 at cruise mode), representing various twist angles ranging from −14° to +14°, incremented symmetrically around the baseline (0°). This range was chosen to capture both beneficial and adverse aerodynamic behaviours induced by positive and negative twist. The twist was applied beginning at a radial position of 0.85 r/R, where r/R denotes the spanwise location normalised by the rotor radius. This region, near the blade tip, is known to be aerodynamically dominant due to higher relative velocity caused by rotational motion. Prior studies [2, 4] have identified this outboard region as the most effective for implementing aerodynamic control strategies, including passive and active morphing devices.

2.1 Governing Equations and Turbulence Modelling

The aerodynamic performance of the rotor blade configurations was analysed using the Reynolds-Averaged Navier–Stokes (RANS) equations, which are derived from the incompressible Navier–Stokes equations by decomposing the instantaneous flow variables into mean and fluctuating components. This averaging process allows for the prediction of turbulent flows without resolving the full spectrum of turbulence scales, significantly reducing computational cost while retaining sufficient accuracy for engineering applications. The time-averaged momentum equation in the RANS framework is expressed as:

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j^2} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \quad \textbf{(1)}$$

Here, the final term $-\frac{\partial \overline{u_i' u_j'}}{\partial x_j}$ represents the Reynolds stresses, which encapsulate the effects of turbulence. This introduces a closure problem that necessitates the use of a turbulence model to approximate the Reynolds stress tensor. To address this, the k–ω Shear Stress Transport (SST) model was employed. The k–ω SST model is a two-equation eddy-viscosity model that solves transport equations for the turbulent kinetic energy (k) and the specific dissipation rate (ω). It combines the accuracy of the standard k–ω model in the near-wall region with the free-stream robustness of the k–ε model, achieved through a blending function. The governing equations for the k–ω SST model are given as:

- Turbulent kinetic energy (k)

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] \quad \textbf{(2)}$$

- Specific dissipation rate (ω):

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad \textbf{(3)}$$

In these equations, Pk denotes the production of turbulent kinetic energy, νt is the eddy viscosity, and F1 is a blending function that transitions between the k–ω and k–ε behaviours. This model is particularly suited for flows with adverse pressure gradients and boundary layer separation, which are common in rotor blade aerodynamics.

2.2 Mesh-Sensitivity Study and CFD Setup

To ensure the accuracy and reliability of the CFD results, a mesh sensitivity analysis was conducted as part of the numerical verification process. Computational grids of varying densities were generated, ranging from approximately 400,000 to 3 million cells (Figure 1.b and Figure 1.c), to evaluate the influence of mesh resolution on key aerodynamic outputs, particularly the lift-to-drag ratio (CL/CD). Structured and semi-structured hexahedral-dominant meshes were used with local refinement near the blade surface and in the wake region to capture boundary layer behaviour and flow separation. A consistent y^+ value below 1 was maintained in the near-wall regions to support the requirements of the k–ω SST turbulence model. The analysis showed that the predicted aerodynamic coefficients exhibited strong mesh dependency below 1 million elements. However, beyond this threshold, the variation in the calculated CL/CD ratio between successive refinements was consistently below 2%, indicating that mesh convergence had been achieved. Consequently, all production simulations were conducted using meshes with approximately 1.5 to 2 million elements, balancing computational cost with solution fidelity. This mesh convergence study provides confidence in the resolution of key flow features, particularly in the morphing region near the blade tip, and validates the fidelity of the comparative performance analysis across the examined twist configurations.

The Multiple Reference Frame (MRF) approach was employed to a cylindrical rotating zone, centred at y = –0.05 m with a radius of 10.5 m (i.e. ~ 10% larger than rotor radius) and height of 1.2 m, was aligned along the y-axis to capture rotational effects. This region was embedded in a larger stationary domain (i.e. flow region) extending from x = –50 m to +50 m, y = –200 m to +150 m, and z = –50 m to +50 m, ensuring minimal boundary influence (simulating a large-scale wind tunnel) see Figure 1.a. The MRF zone was configured with a rotational velocity of 203 RPM to represent the operating hover conditions of the rotor blade.

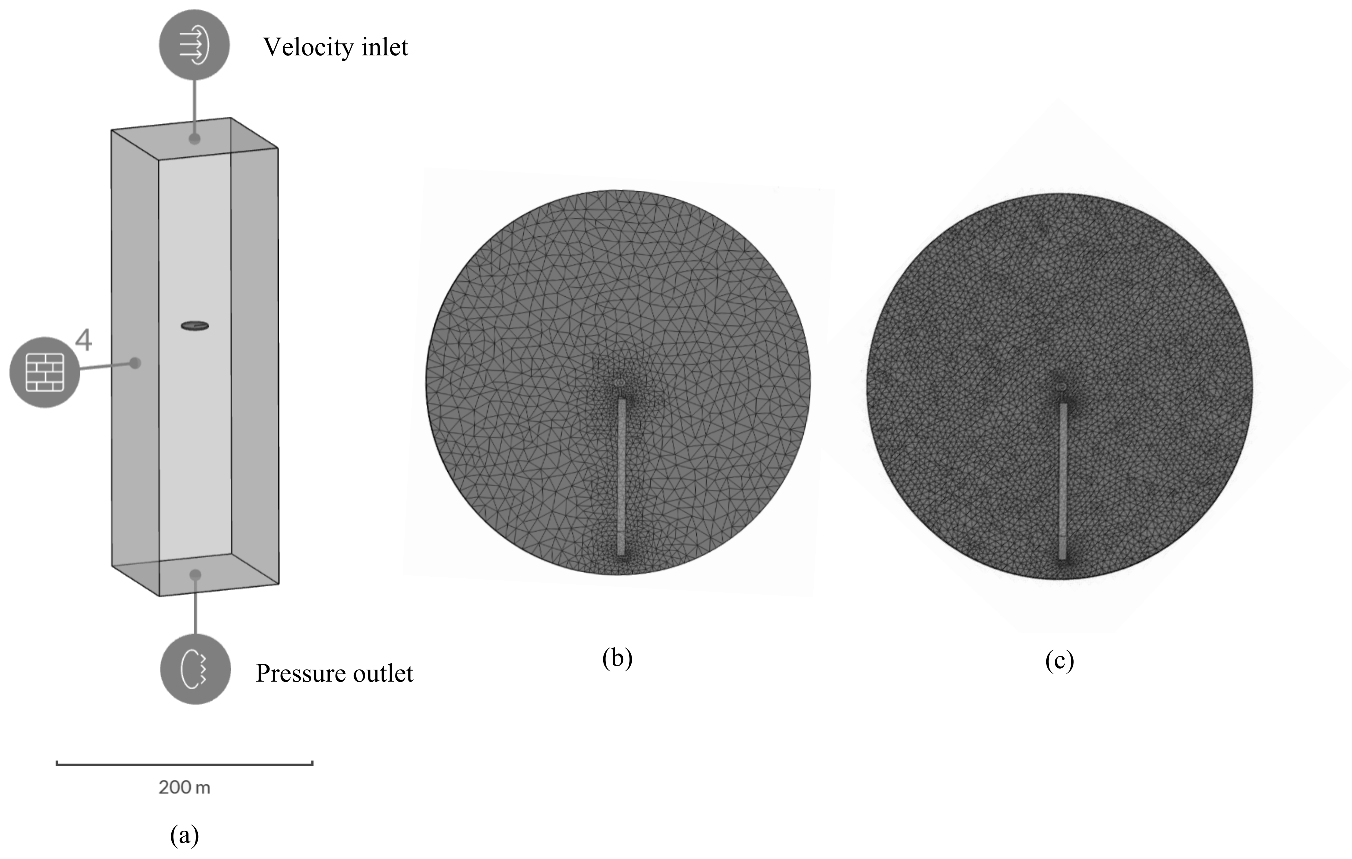

Figure 1: (a) Illustrating the environment setup with velocity inlet – pressure outlet coupling (b) Coarse mesh (c) Finer mesh

3. Morphing Analysis

3.1 Hover

Table 2 outlines the key input parameters defined for the rotor blade operating under hover conditions. According to established rotorcraft aerodynamics literature, particularly Johnson (1980), angles of attack near the outboard sections typically fall within the range of 10° to 15°, depending on blade geometry, inflow distribution, and operating conditions. Based on this, a baseline angle of attack of 12° was selected for this study where it can meet the criteria for balancing the lift and weight forces.

Table 2: Baseline operating parameters and environmental conditions for rotor blade in hover

RPM	AOA	Radius	Chord	Freestream	Airfoil	Atmospheric conditions
203	12°	8.7 m	0.44 m	1 m/s	NACA0012	SLS

Figure 2 presents the resulting trends in aerodynamic efficiency, expressed as the percentage increase in lift-to-drag across the full set of morphing cases. The analysis reveals how geometric twist in the outer blade region can lead to measurable gains or penalties in aerodynamic performance, depending on the direction and magnitude of the applied twist. These results provide critical insight into the trade-offs associated with implementing spanwise twist morphing and help quantify its potential as a viable aerodynamic enhancement strategy for rotorcraft in hover.

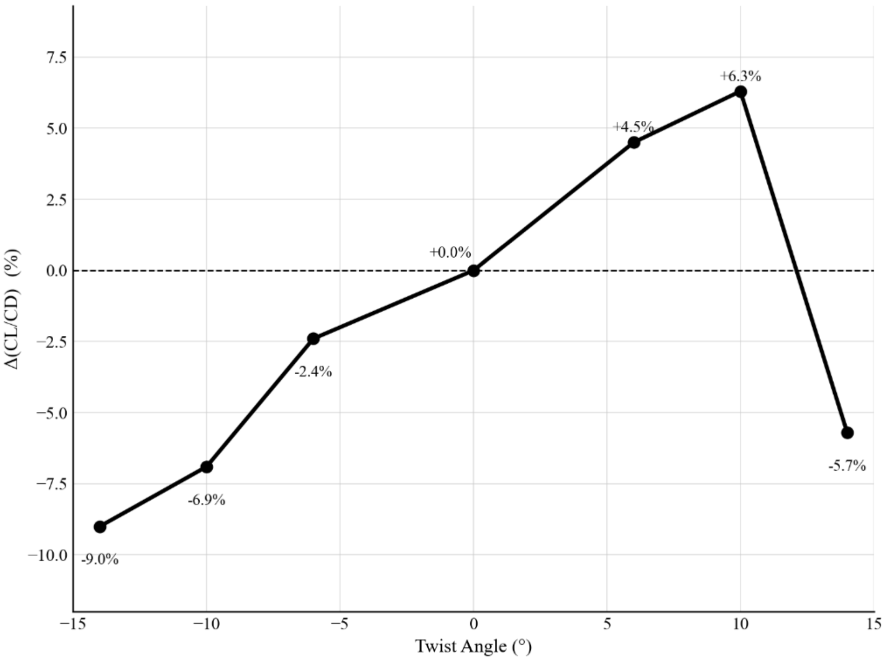

Figure 2: The effects of positive and negative full chord twist morphing on the rotor blade's aerodynamic efficiency at 0.85 r/R spanwise location

As anticipated and consistent with existing literature, positive twist angles generally enhance aerodynamic efficiency. This is due to a more favourable angle of attack distribution along the blade span. Specifically, twist angles of +6° and +10° yielded efficiency gains of 4.5% and 6.3%, respectively, relative to the 0° baseline. However, this improvement does not continue indefinitely. At +14°, the efficiency drops significantly (–5.7%), indicating a nonlinear response beyond a certain twist threshold. This reversal is likely attributable to localised flow separation or stall effects near the blade tip, where the combination of embedded design twist (+12° for hover mode) and added twist becomes excessive. Conversely, negative twist angles reduce aerodynamic efficiency across the board, with –14° causing the largest drop (–9.0%). This is expected, as under-twisted blades reduce lift and increase drag by misaligning the blade's local flow direction with the incoming air.

3.2 Cruise

The cruise flight envelope imposes a distinct aerodynamic environment compared to hover, necessitating tailored considerations in blade design to sustain efficient performance. The configuration parameters utilised in this investigation are outlined in Table 3. Informed by foundational rotorcraft aerodynamic theory (Johnson, 1980), the outer blade sections in cruise are known to operate at moderate angles of attack, typically between 5° and 10°, subject to blade planform, twist gradient, and induced inflow distribution. Accordingly, an angle of attack of 7° was selected as the baseline reference condition in this study. This choice represents a compromise solution that enables the rotor to satisfy lift requirements while mitigating the onset of drag penalties and maintaining aerodynamic stability across the span. The selected value ensures consistency with typical operational envelopes reported in both theoretical analyses and empirical rotorcraft data. Deviations from this baseline were introduced via twist modifications, with the objective of evaluating their impact on aerodynamic efficiency.

Table 3: Baseline operating parameters and environmental conditions for rotor blade in cruise

RPM	AOA	Radius	Chord	Freestream	Airfoil	Atmospheric conditions
203	7°	8.7 m	0.44 m	50 m/s	NACA0012	SLS

Under cruise conditions, the aerodynamic response of the rotor blade exhibits a pronounced sensitivity to spanwise twist, a phenomenon primarily driven by the significantly increased inflow velocity compared to hover. In the present study, the freestream velocity in cruise was set at 50 m/s, in stark contrast to the near-static inflow of 1 m/s in hover. This higher freestream component leads to substantially increased relative flow velocities along the blade, particularly towards the outer span, thereby amplifying the influence of geometric modifications. Figure 3 presents the corresponding velocity contours, which clearly demonstrate the enhanced local velocities in the tip region during cruise once compared to the hover mode. It additionally represents the turbulence for the two flight segments (hover vs cruise) both at +14° of twist with the cruise profile showcasing a fully turbulent flow. Therefore, quantitative analysis indicates that aerodynamic efficiency exhibits greater improvements in response to positive twist under cruise conditions. A +14° twist results in a 31% increase in CL/CD, while +10° and +6° introduce improvements of 12.85% and 1.3%, respectively, relative to the baseline configuration. These findings demonstrate a nonlinear but positively correlated relationship between twist angle and aerodynamic performance, suggesting that cruise efficiency is highly susceptible to beneficial geometric tailoring. Notably, the magnitude of improvement observed under cruise far exceeds that recorded in hover, which is consistent with the enhanced aerodynamic loading due to increased dynamic pressure at higher freestream velocities.

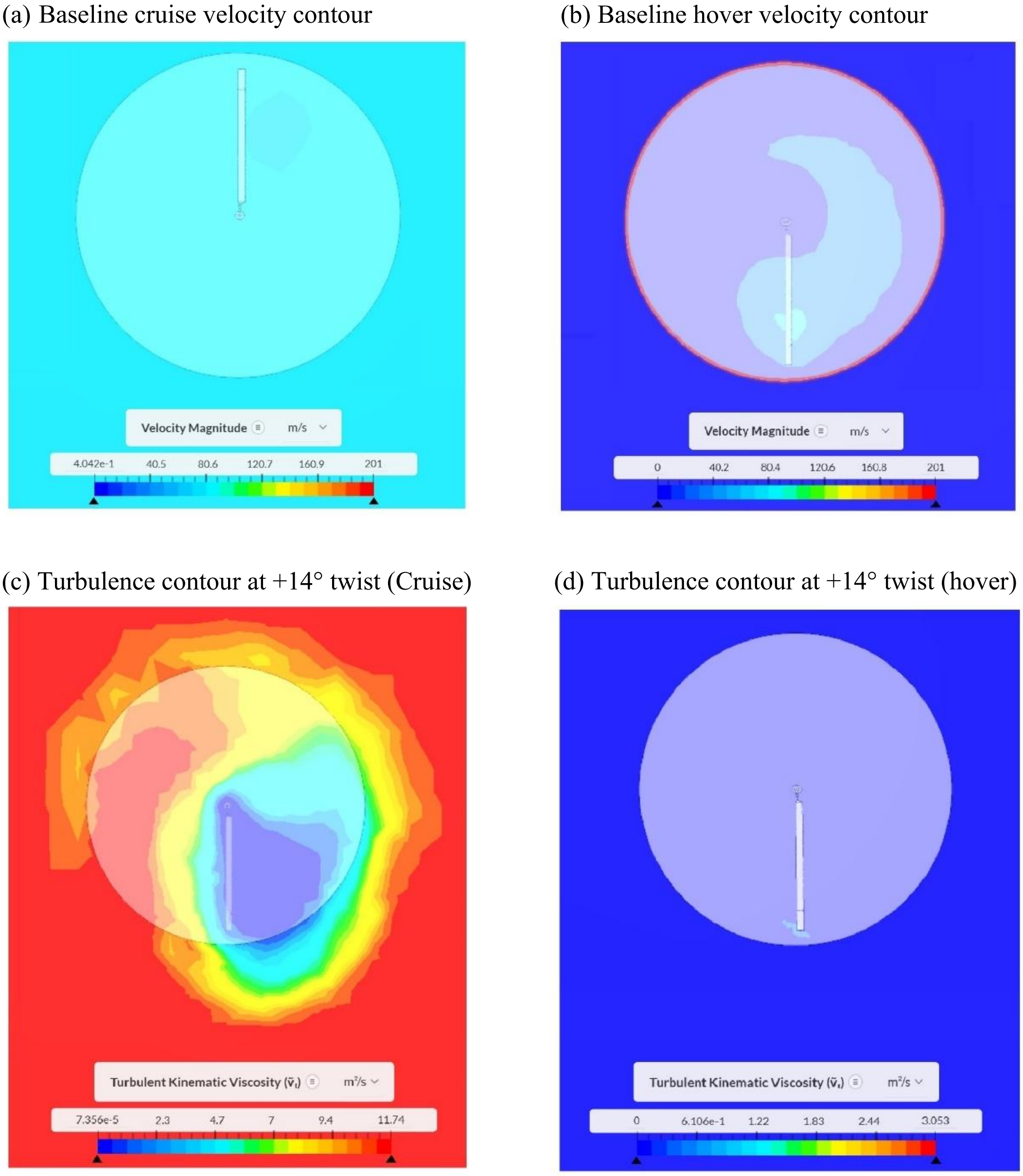

Figure 3: Illustrating the baseline velocity contours at cruise (a), hover (b) and turbulence contours with +14° of twist at cruise (c) and hover (d)

4. Conclusions

This investigation explored the aerodynamic implications of partial spanwise twist morphing in rotorcraft blades, with a particular focus on the performance differential across hover and cruise flight regimes. A high-fidelity RANS-based CFD approach was employed to assess the effects of full-chord twist introduced at 0.85 r/R on a baseline Sea King rotor blade, with twist magnitudes ranging from –14° to +14°. The findings provide compelling evidence that twist morphing represents a viable aerodynamic enhancement mechanism capable of adapting blade performance to distinct flight conditions. In hover, moderate positive twist angles provided increases in aerodynamic efficiency, with the +10° configuration improving CL /CD by 6.3%. As expected, negative twist angles universally reduced efficiency due to suboptimal flow alignment and diminished lift production. Cruise conditions revealed significantly greater sensitivity to twist variations. Here, the interaction between geometric modification and the increased freestream velocity (50 m/s) resulted in a more pronounced response in lift-to-drag ratio. The +14° twist case delivered a substantial 31%

improvement in aerodynamic efficiency, while +10° and +6° achieved 12.85% and 1.3% gains, respectively. This trend correlates with increased local flow velocities, particularly near the outboard regions, as visualised in the velocity and turbulence contour fields. Overall, the results strongly support the integration of twist-morphing mechanisms into future rotorcraft platforms. The non-linear relationship between twist and aerodynamic performance across both flight regimes underscores the importance of optimising twist magnitude and distribution in a flight-phase-specific manner. While this study provides clear aerodynamic justification for twist morphing, it also sets the stage for subsequent investigations into the structural, aeroelastic, and actuation challenges associated with real-time morphing implementation. Addressing these multidisciplinary aspects will be essential to transitioning twist-morphing blades from conceptual promise to operational reality in next-generation rotary-wing systems.

Acknowledgements

The authors acknowledge SimScale GmbH for the provision of an academic licence, along with supplementary core hours and computational resources, which facilitated the completion of this study.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

The data underlying the findings of this study are available from the corresponding author upon reasonable request.

ORCID iD
Mars Burke https://orcid.org/0000-0001-9793-2426

References

[1] Woodgate, M. A., V. A. Pastrikakis, and G. N. Barakos. 2016. Method for calculating rotors with active Gurney flaps. *AIAA J.* 53(3):605–626.
[2] Gagliardi, A., and G. N. Barakos. 2009. Analysis and design of a flap-equipped low-twist rotor for hover. *J. Aircraft* 46(1):251–259.
[3] Huang, Q., A. Abdelmoula, G. Chourdakis, J. Rauleder, and B. Uekermann. 2021. CFD/CSD coupling for an isolated rotor using preCICE. In: *Proc. WCCM-ECCOMAS Congress*.
[4] Khoshlahjeh, M., and F. Gandhi. 2014. Extendable chord rotors for helicopter envelope expansion and performance improvement. *J. Am. Helicopter Soc.* 59:012007.
[5] Martin, P., K. McAlister, M. Chandrasekhara, and W. Geissler. 2003. Dynamic stall measurements and computations for a VR-12 airfoil with a variable droop leading edge. In: *59th American Helicopter Society Forum*, Phoenix, AZ, May 6–8.
[6] SimScale: Cloud-based engineering simulation. https://www.simscale.com/ (accessed June 1, 2025).