RCMOS – Revista Científica Multidisciplinar O
Saber. ISSN: 2675-9128. São Paulo - SP.
Ano VII, v.1 2026 | submissão: 15/08/2026 | aceito: 18/08/2026 | publicação: 21/08/2026

Fundamentals of wind-turbine aerodynamics: lift principles and efficiency in wind rotors

Fundamentos em aerodinâmica de aerogeradores: princípios de sustentação e eficiência em rotores eólicos

Fundamentos de aerodinámica de aerogeneradores: principios de sustentación y eficiencia en rotores eólicos

Lucas Emanuel Almeida Barboza

Abstract:
Efficient extraction of wind kinetic energy by a wind turbine is fundamentally an aerodynamic challenge. This article presents a qualitative literature review aimed at analyzing the aerodynamic fundamentals applied to wind rotors, with emphasis on lift and drag forces. The methodology is based on an integrative literature review that covers classic works of aeronautical engineering adapted to the wind sector and recent publications on blade design. The results indicate that the performance of a horizontal-axis wind turbine is dictated by the geometry of its airfoils and by the relationship between blade-tip speed and wind speed (tip-speed ratio - TSR). It is concluded that maximizing the lift-to-drag ratio is essential to increasing the power coefficient and directly affects the feasibility and cost of the energy generated.

Keywords:
Aerodynamics. Wind turbines. Airfoil. Lift force. Drag.

Resumo:
A extração eficiente da energia cinética dos ventos por um aerogerador é fundamentalmente um desafio aerodinâmico. O presente artigo apresenta uma revisão bibliográfica qualitativa com o objetivo de analisar os fundamentos de aerodinâmica aplicados aos rotores eólicos, com ênfase nas forças de sustentação e arrasto. A metodologia fundamenta-se em uma revisão integrativa da literatura, abordando obras clássicas de engenharia aeronáutica adaptadas para o setor eólico e publicações recentes sobre design de pás. Os resultados indicam que o desempenho de uma turbina eólica de eixo horizontal é ditado pela geometria de seus perfis aerodinâmicos (airfoils) e pela relação entre a velocidade da ponta da pá e a velocidade do vento (Tip Speed Ratio - TSR). Conclui-se que a maximização da razão sustentação-arrasto é essencial para o aumento do coeficiente de potência, influenciando diretamente a viabilidade e o custo da energia gerada.

Palavras-chave:
Aerodinâmica. Aerogeradores. Perfil aerodinâmico. Força de sustentação. Arrasto.

Resumen:
La extracción eficiente de la energía cinética del viento mediante un aerogenerador es fundamentalmente un desafío aerodinámico. Este artículo presenta una revisión bibliográfica cualitativa cuyo objetivo es analizar los fundamentos de aerodinámica aplicados a los rotores eólicos, con énfasis en las fuerzas de sustentación y arrastre. La metodología se fundamenta en una revisión integradora de la literatura que aborda obras clásicas de ingeniería aeronáutica adaptadas al sector eólico y publicaciones recientes sobre diseño de palas. Los resultados indican que el desempeño de una turbina eólica de eje horizontal está determinado por la geometría de sus perfiles aerodinámicos y por la relación entre la velocidad de la punta de la pala y la velocidad del viento (Tip Speed Ratio - TSR). Se concluye que maximizar la relación

sustentación-arrastre es esencial para aumentar el coeficiente de potencia e influye directamente en la viabilidad y el costo de la energía generada.

Palabras clave:
Aerodinámica. Aerogeneradores. Perfil aerodinámico. Fuerza de sustentación. Arrastre.

1. Introduction

The rotor of a modern wind turbine acts as the primary interface between the moving fluid (wind) and the mechanical generation system. Unlike old wind wheels or drag-based windmills, contemporary horizontal-axis wind turbines operate according to principles very similar to those of aircraft wings and seek maximum energy-extraction efficiency (HANSEN, 2015). Blade design is one of the most complex and closely guarded fields of wind engineering because small surface optimizations can produce significant gains in energy generation over decades of operation (BURTON et al., 2011). In this context, this study aims to review the fundamental aerodynamic principles applied to wind turbines and to detail how fluid-structure interaction results in torque generation and power control.

2. Theoretical framework

2.1. Aerodynamic forces: lift and drag

When airflow crosses the airfoil (cross-section) of a wind-turbine blade, it is divided into two paths: the pressure side (lower surface) and the curved suction side (upper surface). In the classical formulation based on Bernoulli's principle, the upper curvature accelerates airflow and reduces static pressure on that surface. The pressure difference between the lower and upper surfaces produces a resulting force perpendicular to the flow, known as lift (ANDERSON, 2011). At the same time, friction between the air and blade surface, together with the turbulent wake left by the profile, produces a force parallel to the flow direction known as drag. For high-performance wind turbines, aerodynamic design seeks to maximize lift, which generates useful torque, and minimize drag as much as possible (MANWELL; MCGOWAN; ROGERS, 2010).

2.2. Tip-speed ratio (TSR)

The aerodynamic interaction of a wind rotor depends not only on free-stream wind speed but also on the rotational speed of the blade itself. This balance is quantified by the tip-speed

ratio (TSR), which relates the tangential speed of the blade tip to the incident wind speed (PINTO, 2013). If the rotor turns too slowly (low TSR), most of the wind passes freely between the blades without aerodynamic interaction. If it turns too quickly (high TSR), the blades act like a solid wall, blocking the flow and creating severe turbulence. Therefore, every rotor geometry has an optimal TSR that maximizes its aerodynamic power coefficient (HANSEN, 2015).

3. Materials and method

The research consists of an integrative literature-review study with a qualitative approach. The theoretical foundation was built by selecting textbooks on general aerodynamics and wind engineering, complemented by scientific articles discussing the evolution of airfoils and comprising publications from 2010 to 2024. The documentary-analysis method focused on isolating the physical phenomena governing energy conversion and categorizing them into torque-generation processes and aerodynamic power-limitation mechanisms.

4. Results and discussion

The literature findings reveal that modern wind-turbine aerodynamics has shifted from traditional aircraft profiles, such as the NACA series, toward profiles developed specifically for turbine operating conditions, which involve higher turbulence levels and varying angles of attack (BURTON et al., 2011). One relevant operational issue is stall. When the wind's angle of attack relative to the blade reaches a critical value, airflow separates from the blade's suction side, causing lift to fall sharply and drag to increase (ANDERSON, 2011). Historically, turbines used passive aerodynamic stall as a safety measure to slow the rotor in extreme winds. Current literature, however, highlights the predominance of pitch control, in which motors rotate the blade about its own axis and dynamically change the angle of attack to maintain continuous aerodynamic efficiency or induce braking in a controlled manner.

5. Final considerations

The study concludes that aerodynamics is the foundational science of wind-turbine performance and is directly responsible for the efficiency with which wind is transformed into mechanical motion. Refining lift forces and optimizing management of the tip-speed ratio

(TSR) are critical parameters for maximizing energy extraction. As a contribution, this article synthesizes the transition from pure aerodynamic concepts to their practical application in power control. Future studies should investigate aeroelasticity - how the physical deformation of giant blades under extreme wind loads affects their aerodynamics - an increasingly important challenge in the design of modern turbines whose blades already exceed 100 meters in length.

References

ANDERSON, John D. Fundamentals of Aerodynamics. 5. ed. New York: McGraw-Hill Education, 2011.

BURTON, Tony et al. Wind Energy Handbook. 2. ed. Chichester: John Wiley & Sons, 2011.

HANSEN, Martin O. L. Aerodynamics of Wind Turbines. 3. ed. London: Routledge, 2015.

MANWELL, James F.; MCGOWAN, Jon G.; ROGERS, Anthony L. Wind Energy Explained: Theory, Design and Application. 2. ed. Chichester: John Wiley & Sons, 2010.

PINTO, Milton de Oliveira. Fundamentos de Energia Eólica. Rio de Janeiro: LTC, 2012.