A comparative analysis of rotating airfoils focusing on aerodynamic performance and airflow patterns through 2D unsteady simulations

Uma análise comparativa de aerofólios rotativos com foco no desempenho aerodinâmico e nos padrões de fluxo de ar por meio de simulações 2D instáveis

DOI: 10.54021/seesv5n1-143
Recebimento dos originais: 10/05/2024
Aceitação para publicação: 31/05/2024

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ABSTRACT
The blade section of a wind turbine plays a pivotal role in harnessing the power of the wind to generate clean and renewable energy. Each turbine blade is carefully designed with specific aerodynamic principles in mind, primarily focusing on lift and drag forces. Understanding the intricacies of aerodynamics in this context is crucial for optimizing energy capture and ensuring the overall efficiency of wind power systems. In this context the present paper investigates the aerodynamics of three airfoils named NACA-4412, NACA-23012, and NACA-63415 using numerical simulations performed with Ansys Fluent software, with a specific focus on performance and airflow patterns. Through two-dimensional unsteady simulations, the computational approach thoroughly explores the impact of rotational speeds (ranging from 2 to 16 degrees per second) and a range of Reynolds numbers from 1.25e6 to 2e6. The findings illustrate the dynamic interplay between airflow patterns and operational factors. Variations in velocity magnitude, influenced by rotational speeds and Reynolds numbers, were observed. These variations provided additional insights into flow behavior near the airfoil, including the identification of flow separation regions, as depicted by the velocity vectors. Analysis of lift coefficient values revealed a minimal variation concerning changes in rotational speed, suggesting 8 degrees per second as an appropriate rotational speed for the studied cases. Examination of airfoil aerodynamic coefficient trends highlighted noteworthy findings. Drag coefficient values exhibited an increasing variation over time, with higher values observed in the case of the NACA-63415.
airfoil. On the other hand, lift coefficient values displayed an increasing variation reaching a maximum value, followed by a decreasing trend. Notably, the NACA 4412 airfoil demonstrated superior aerodynamic coefficients compared to the other studied airfoils.

**Keywords:** airfoil, performance and airflow patterns, airfoil drag and lift coefficients, rotational speeds, angles of attack, two-dimensional unsteady simulations.

**RESUMO**
A seção da pá de uma turbina eólica desempenha um papel fundamental no aproveitamento da força do vento para gerar energia limpa e renovável. Cada lâmina de turbina é cuidadosamente projetada com princípios aerodinâmicos específicos em mente, concentrando-se principalmente nas forças de sustentação e arrasto. Compreender os meandros da aerodinâmica nesse contexto é fundamental para otimizar a captação de energia e garantir a eficiência geral dos sistemas de energia eólica. Nesse contexto, o presente artigo investiga a aerodinâmica de três aerofólios denominados NACA-4412, NACA-23012 e NACA-63415 usando simulações numéricas realizadas com o software Ansys Fluent, com foco específico no desempenho e nos padrões de fluxo de ar. Por meio de simulações bidimensionais instáveis, a abordagem computacional explora minuciosamente o impacto das velocidades de rotação (variando de 2 a 16 graus por segundo) e uma gama de números de Reynolds de 1,25e6 a 2e6. Os resultados ilustram a interação dinâmica entre os padrões de fluxo de ar e os fatores operacionais. Foram observadas variações na magnitude da velocidade, influenciadas pelas velocidades de rotação e pelos números de Reynolds. Essas variações forneceram informações adicionais sobre o comportamento do fluxo próximo ao aerofólio, incluindo a identificação de regiões de separação de fluxo, conforme descrito pelos vetores de velocidade. A análise dos valores do coeficiente de sustentação revelou uma variação mínima em relação às mudanças na velocidade de rotação, sugerindo 8 graus por segundo como uma velocidade de rotação apropriada para os casos estudados. O exame das tendências do coeficiente aerodinâmico do aerofólio destacou descobertas dignas de nota. Os valores do coeficiente de arrasto apresentaram uma variação crescente ao longo do tempo, com valores mais altos observados no caso do aerofólio NACA-63415. Por outro lado, os valores do coeficiente de sustentação apresentaram uma variação crescente, atingindo um valor máximo, seguido de uma tendência decrescente. Notavelmente, o aerofólio NACA 4412 demonstrou coeficientes aerodinâmicos superiores em comparação com os outros aerofólios estudados.

**Palavras-chave:** aerofólio, desempenho e padrões de fluxo de ar, coeficientes de arrasto e sustentação do aerofólio, velocidades rotacionais, ângulos de ataque, simulações bidimensionais não estáveis.

**1 INTRODUCTION**

The blade section of a wind turbine is essential for converting wind into...
clean, renewable energy. Each blade is meticulously designed based on aerodynamic principles, with a focus on lift and drag forces. Grasping the details of aerodynamics in this setting is vital for maximizing energy capture and ensuring the efficiency of wind power systems. (LEIFSSON; KOZIEL, 2015; SHARMA; GUPTA; PANDEY; SHARMA et al., 2021). In the literature, Numerous studies by (ALMOHAMMADI, 2022; BAYRAM, 2022; ERKAN; ÖZKAN; KARAKOÇ; GARRETT et al., 2020; GÖRGÜLÜ; ÖZGÜR; KÖSE, 2021; GÖV; DOĞRU, 2020; KOCA; GENÇ; AÇIKEL; ÇAĞDAŞ et al., 2018; OUKASSOU; EL MOUHSINE; EL HAJJAJI; KHARBOUCH, 2019; TEFERA; BRIGHT; ADALI, 2022; YıLMAZ; KÖTEN; ÇETINKAYA; COŞAR, 2018) have scrutinized the aerodynamic behaviors of NACA airfoils. These analyses encompass a variety of blade section forms, including NACA0012, NACA4412, NACA2412, NACA0009, NACA4415, NACA0015, and NACA63415. Employing a range of methodologies, from experimental to numerical approaches. The outcomes of these studies aim to identify optimal points encompassing blade section form, lift (CL) and drag (CD) coefficients, Pressure coefficient, Reynolds number from low to high, and angle of attack. The studies by (NIROOEI, 2018; OCKFEN; MATVEEV, 2009; QU; HUANG; LIU; HU et al., 2017; QU; JIA; WANG; AGARWAL et al., 2014; QU; JIA; WANG; LIU et al., 2014; QU; WANG; LIU; AGARWAL, 2015; SUTARDI; FUAD, 2023) collectively investigate the aerodynamic behavior of airfoils, particularly the NACA4412, under various conditions such as dynamic ground effect, extreme ground effect. Utilizing numerical simulations, experimental methods, and computational modeling techniques, these works elucidate intricate flow characteristics, pressure distributions, lift and drag forces, and their dependencies on factors like angle of attack, Reynolds number, and ground clearance. In order to that the wavy ground effects on the aerodynamic characteristics and flow field of NACA airfoils are examined in works of (HU; MA, 2020; LEE; TREMBLAY-DIONNE, 2018; LIU; MA; YANG; GUO et al., 2021; ZHI; XIAO; CHEN; WU et al., 2019). The present study provides a comparative analysis of the aerodynamics of three airfoils named NACA-4412, NACA-23012, and NACA-63415 with a specific focus on aerodynamic performance and airflow patterns, through two-dimensional unsteady simulations using Ansys Fluent software, the computational approach thoroughly explores the impact of rotational speeds (ranging from 2 to 16 degrees
per second) and a range of Reynolds numbers from 1.25e6 to 2e6.

2 NUMERICAL METHODOLOGY

The numerical methodology employed in this study consists of four main steps. Firstly, the domain is created using the Design Modeler tool. In the second step, a computational mesh is generated. The third step involves configuring the solver using ANSYS Fluent. Finally, the results are subjected to post-processing.

3 GOVERNING EQUATIONS

The flow is governed by the unsteady-state Reynolds-Averaged Navier-Stokes (RANS) equations, describing momentum conservation, together with requirement for mass conservation (ALFONSI, 2009), the two relevant expressions are given by, respectively,

Continuity:

\[ \frac{\partial \overline{u}_i}{\partial x_i} = 0 \]  

Momentum:

\[ \frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_i} \left( -\overline{u}_i \overline{u}_j \right) \]
In Equation (2), \( \bar{p} \) represents mean pressure, \( \nu \) stands for the fluid kinematic viscosity, and \( \overline{-u_i'u_j'} \) denotes the Reynolds stresses. To accurately address turbulence effects, Reynolds stresses are modelled in order to achieve closure of Equation (2). The method of modelling employed utilises the Boussinesq hypothesis to relate the Reynolds stresses to the mean velocity gradients within the flow. In order to that the study employs the K-Omega SST turbulence model (NICHOLS, 2010).

4 COMPUTATIONAL DOMAIN AND CALCULATION MESH

The constructed domain is partitioned into an inner circular shape (with a diameter five times that of the chord length) for accommodating variations in the angle of attack. Additionally, there is an outer domain featuring inlet and outlet boundaries. Within this entire domain, a structured mesh is generated, as depicted in Figure 2.

![Figure 2: Computational domain.](source: Authors)

5 RESULTS AND DISCUSSION

A mesh sensitivity analysis was conducted to verify the suitability of the mesh for the simulations. The results, depicted in Table 1, indicated that the optimal number of mesh cells for the current study was 31030 cells. This value was utilized to generate the final mesh for the simulations. An analysis of time step variation including three values (Dt=0.002, Dt=0.02, and Dt=0.2s) revealed the use of Dt=0.02s for the current simulations (see Table 2). Additionally, the Figure presents a comparison between the numerical findings of this study and
experimental data (COLES; WADCOCK, 1979) and numerical results (TAGAWA; MORENCY; BEAUGENDRE, 2018) to validate the numerical approach used in the present study. The comparison revealed an acceptable agreement between the datasets.

Table 1: Mech cells variation analysis

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>51569 Cells</th>
<th>31030 Cells</th>
<th>17648 Cells</th>
<th>Err %</th>
<th>Err %2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>0.582</td>
<td>0.579</td>
<td>0.578</td>
<td>0.43%</td>
<td>0.13%</td>
</tr>
<tr>
<td>3.000</td>
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<td>0.957</td>
<td>0.957</td>
<td>0.32%</td>
<td>-0.06%</td>
</tr>
<tr>
<td>6.000</td>
<td>1.447</td>
<td>1.447</td>
<td>1.440</td>
<td>0.02%</td>
<td>0.46%</td>
</tr>
<tr>
<td>9.000</td>
<td>1.674</td>
<td>1.690</td>
<td>1.652</td>
<td>-0.92%</td>
<td>2.25%</td>
</tr>
<tr>
<td>11.500</td>
<td>1.444</td>
<td>1.479</td>
<td>1.414</td>
<td>-2.42%</td>
<td>4.38%</td>
</tr>
</tbody>
</table>

Source: Authors

Table 2: Time step variation analysis

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>DT = 0.002</th>
<th>DT = 0.02</th>
<th>DT = 0.2</th>
<th>Err %</th>
<th>Err %2</th>
</tr>
</thead>
<tbody>
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<td>0.579</td>
<td>0.582</td>
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<td>-0.567%</td>
</tr>
<tr>
<td>3.000</td>
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<td>0.958</td>
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<td>1.439</td>
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<tr>
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<td>1.690</td>
<td>1.631</td>
<td>-0.505%</td>
<td>3.492%</td>
</tr>
<tr>
<td>11.000</td>
<td>1.528</td>
<td>1.479</td>
<td>1.460</td>
<td>3.208%</td>
<td>1.300%</td>
</tr>
</tbody>
</table>

Source: Authors

Figure 3: Numerical approach Validation.

Figure 4 illustrate graphs of the lift coefficient as a function of the angle of attack within the specified range of [0 to 23 degrees] at a Reynolds number of 2e6. The analysis focuses on the NACA-4412 airfoil, incorporating a range of rotational speeds (from 2 to 16 degrees per second). From these figures, it is evident that there is a small variation in lift coefficient values concerning the change in rotational
speed, allowing for the selection of 8 degrees per second as the accepted rotational speed for the remaining studied cases.

Figure 4: Lift coefficient in function of angle of attack.

Figures 5 and 6 illustrate graphs of drag and lift coefficients as functions of time for the specified range of [0 to 3s] and several Reynolds numbers (1.25e6, 1.5e6, 1.75e6, and 2e6). Within the utilized rotational speed of 8 degrees per second, the analysis encompasses a range of angles of attack (from 0 to 23 degrees). In order to that the analysis considered three airfoils named NACA-4412, NACA-23012, and NACA-63415, from these figures, it is clear that the lift coefficient values exhibit an increasing variation to a maximum value after that a decreasing trend can be noticeable, the maximum values are 1.67 at 2.28 (s), 1.45 at 2.22 (s) and 1.33 at 1.9 (s), which correspond to 18.24, 17.76 and 15.2 degrees for the airfoil NACA-4412, NACA-23012, and NACA-63415, respectively. In order to that the drag coefficient values exhibit an increasing variation over time with high values in the case of NACA-63415.
Figures 7 and 8 present visualizations of velocity magnitude and velocity vectors, examining the aerodynamic characteristics of three airfoils named NACA-4412, NACA-23012, and NACA-63415. Within these figures, twelve images are displayed, illustrating different angles of attack (17.28 and 23.04 degrees) at a Reynolds number of 2E6. A noteworthy observation is the presence of a region with minimum values near the trailing edge of the airfoils. This region becomes more pronounced with an increase in the angle of attack, aligning consistently with the flow separation region identified in the velocity vectors.
6 CONCLUSION

In conclusion, this paper delved into the aerodynamics of three airfoils—NACA-4412, NACA-23012, and NACA-63415—employing numerical simulations through Ansys Fluent software. The primary focus of the study was on evaluating performance and airflow patterns. Employing two-dimensional unsteady simulations, the computational approach thoroughly explored the effects of rotational speeds (ranging from 2 to 16 degrees per second) and a range of
Reynolds numbers from 1.25e6 to 2e6. The findings highlighted the dynamic interplay between airflow patterns and operational factors.

Key observations from the study include:

- Variations in velocity magnitude were detected, affected by rotational speeds and Reynolds numbers. These fluctuations gave further insights into flow behavior around the airfoil, such as the discovery of flow separation zones represented by velocity vectors.

- The analysis of lift coefficient values demonstrated a limited variance concerning changes in rotational speed, indicating that 8 degrees per second is an adequate rotational speed for the studied cases.

- An examination of airfoil aerodynamic coefficient trends revealed substantial findings. Drag coefficient values increased over time, with greater values found for the NACA-63415 airfoil. Lift coefficient values, on the other hand, showed increasing variety, peaking at a value and then declining. Notably, the NACA 4412 airfoil has higher aerodynamic coefficients than the other airfoils tested.

Moreover, the study's findings have practical implications for the design and optimization of wind turbine blades. The superior performance of the NACA 4412 airfoil suggests its potential for enhanced energy capture efficiency in wind turbine applications. By understanding the detailed aerodynamic behavior of different airfoils, designers can make informed decisions about blade shape and configuration, leading to more efficient and reliable wind turbines. The comprehensive analysis provided by this paper contributes to the field of wind energy, supporting the development of more effective strategies for harnessing wind power and advancing the goal of sustainable energy production. However, the study has limitations due to its two-dimensional settings, which do not fully capture the complexity of three-dimensional flow effects in wind turbine blades. Additionally, the study focused on a specific range of Reynolds numbers and rotational speeds, which may not cover all operational conditions experienced by wind turbines. This could affect the generalizability of the findings to different wind conditions. Future research should address these limitations through three-dimensional simulations, and a broader range of operational conditions.
REFERENCES


