Public Report

Slender Longer Aerodynamic Blade Enabler (SLABE) - Final Report

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Slender Longer Aerodynamic Blade Enabler (SLABE) - Final Report

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Summary

The Slender Longer Aerodynamic Blade Enabler (SLABE) project was initiated under the TKI Wind op Zee program, part of the Dutch Topsector Energie, to strengthen the competitiveness and innovation capacity of the wind energy sector. The project addressed accurately predicting the aerodynamic performance of flatback airfoils, which enable longer, more slender blades while maintaining structural integrity, a design with growing interest as the industry moves toward ever-larger rotor diameters.

The project brought together five leading wind turbine OEMs in a pre-competitive collaboration demonstrating the value of joint innovation supported by public funding while maintaining confidentiality of proprietary data. TNO coordinated the project as sole developer, while industrial partners contributed as validators and technical advisors through monthly meetings. Partners provided extensive wind tunnel datasets enabling validation and guiding improvements, with TNO supplying a baseline RFOIL version ensuring common reference points.

The project delivered an updated RFOIL version incorporating: (1) modified wake modeling revised for flatback recirculation zones based on high-fidelity simulations across geometries with varying trailing edge thicknesses; (2) enhanced shear stress modeling improving post-stall predictions; and (3) a double wake framework positioned for future completion.

Unfortunately, the consortium faced headwinds from Europe's economic and political landscape. Reorganizations across public and private wind energy groups, including TNO Wind Energy where the majority of the technical team was let go midway, led to severe delays and prevented completing the advanced double wake implementation. Despite these setbacks, the project achieved significant steps forward in understanding and modeling flatback airfoils while maintaining scientific rigor and alignment with national innovation objectives.

All partners received the updated RFOIL tool and confidential validation reports, providing blade designers with more accurate aerodynamic predictions for next-generation turbines. TNO remains committed to RFOIL development through commercial and academic partnerships, prioritizing double wake completion, extending improvements beyond flatbacks, and establishing sustained university-based development frameworks. Partners' continued interest confirms RFOIL's ongoing relevance.

The SLABE project exemplifies both the value and challenges of publicly-funded collaborative research in a rapidly evolving industrial landscape, successfully advancing common aerodynamic modeling knowledge while respecting commercial boundaries and contributing to renewable energy targets.

SLABE has been co-financed by TKI-Energie from the 'Toeslag voor Topconsortia voor Kennis en Innovatie (TKI's)' from the Dutch Ministry of Economic Affairs.

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Abbreviations

DW	Double-Wake
OEMs	Original Equipment Manufacturers
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
TKI	Topsector Kennis en Innovatie (Top Sector Knowledge and Innovation)
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (Netherlands Organisation for applied scientific research)
URANS	Unsteady Reynolds-Averaged Navier-Stokes

1 Introduction

1.1 Background and Motivation

The SLABE project objectives were to improve the predictive capabilities of the airfoil analysis tool RFOIL, with particular focus on the increasingly important class of flatback airfoils. These airfoils are gaining significant traction among Original Equipment Manufacturers (OEMs) as they enable the design of longer, more slender wind turbine blades while maintaining structural integrity. This is a critical requirement as the industry moves toward ever-larger rotor diameters. The blunt trailing edge characteristic of flatback designs offers several distinct advantages: enhanced structural stiffness from the thicker trailing edge region, higher lift coefficients across the operational range, and improved post-stall behavior with more gradual stall characteristics.

These features make flatback airfoils particularly attractive for the inboard sections of modern multi-megawatt blade designs. Yet, these aerodynamic and structural benefits come with a significant challenge: the complex flow patterns around flatback geometries, such as wake shape, size and behavior, vortex shedding, and base pressure effects. These challenges require further development of existing aerodynamic modeling tools, motivating the present work.

1.2 RFOIL

RFOIL is a tool originally developed in 1996 by ECN, TU Delft and NLR as a 'wind turbine modification' of the aerospace code XFOIL [1]. The first version of RFOIL, denoted by RFOIL v1.1, improved the robustness of boundary layer computations, accuracy of predictions near stall, and introduced rotational effects within the boundary layer. A shortcoming of RFOIL v1.1 inherited from XFOIL was the underprediction of the drag coefficient. In 2016, ECN developed a new version of RFOIL, named RFOIL v3.0 [2], which aimed to overcome this drawback. An improvement to lift prediction [3] and a preliminary double wake implementation [4] have been proposed. A simplified algorithm of RFOIL for a standard computation is shown in fig. 1.1.

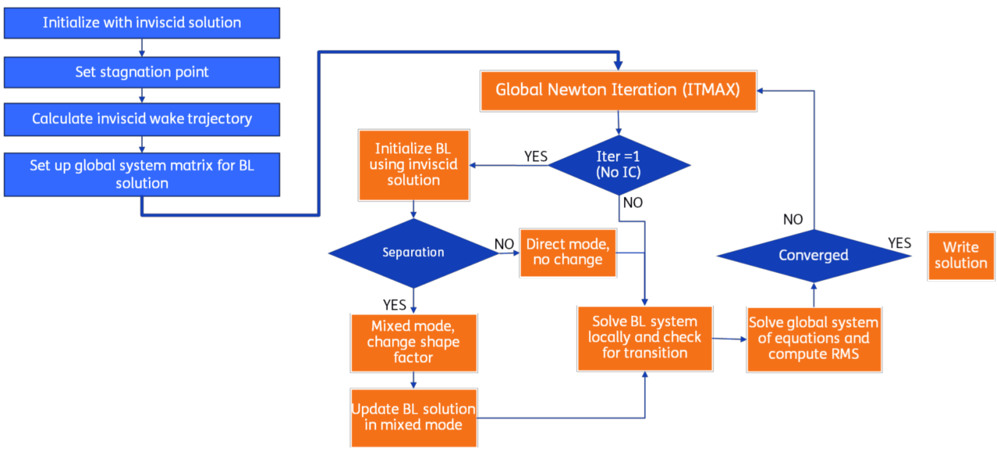

Figure 1.1: RFOIL algorithm showing the iterative solution process for coupled inviscid and viscous flow calculations.

RFOIL operates using a viscous-inviscid interaction approach. While the outer inviscid flow is solved using a panel method based on the potential flow equations, the viscous region is solved using integral boundary layer equations. The latter rely on so-called closure relations which have historically been derived and tuned based on experimental results. This computationally efficient method makes RFOIL particularly suitable for design iteration and optimization workflows, where thousands of airfoil evaluations may be required. To this day, RFOIL remains a tool used extensively by the wind turbine industry in airfoil design and performance analysis.

1.3 Project Objectives

Within this project, improvements to RFOIL were made building upon previous developments along with new modifications specifically targeting flatback airfoil modeling. SLABE proposed several changes to RFOIL:

- A change in the wake modeling to better represent the turbulent boundary layer and the "dead air" region behind flatback foils
- An update in the shear lag equation to improve turbulence modeling in post-stall conditions
- An attempt to implement a double wake functionality to account for separated flow regions

The following chapters detail the project organization, technical developments, validation results, and conclusions from this collaborative research effort.

2 Project Overview

2.1 Data & Consortium

The SLABE project was conceived to address a critical challenge in modern wind turbine blade design: accurately predicting the aerodynamic performance of flatback airfoils. The project was established under the TKI Wind op Zee programme, part of the Dutch Topsector Energie, to advance aerodynamic modelling for wind turbine blades. The project was co-funded by the Dutch government and coordinated by TNO.

- TKI project reference number: TKITOE_WOZ_2302_ECN_SLABE
- Project name: Slender Lighter Aerodynamic Blade Enabler.
- Project consortium: TNO (coordinator), GE Vernova/LM Wind Power, Siemens Gamesa Renewable Energy (SGRE), Nordex, Suzlon, Vestas
- Project period: 01-05-2023 to 31-12-2025

Partner	Type of Organisation	Role in Project
TNO	Research & Development	Coordinator, main investigator, RFOIL development, validation, project management
Vestas	OEM (Industry)	Data provision, validation, technical feedback
Nordex	OEM (Industry)	Data provision, validation, technical feedback
Suzlon	OEM (Industry)	Data provision, validation, technical feedback
LM Wind Power	OEM (Industry)	Data provision, validation, technical feedback
SGRE	OEM (Industry)	Data provision, validation, technical feedback

Table 2.1: SLABE Consortium Partners and Roles

A significant consortium point to be noted is that the main partner contact from SGRE was unfortunately affected by a reorganisation after two-thirds of the project's runtime. A new contact person was appointed in the last days of the project. This unfortunately led to little time and insight for the partner SGRE to give final feedback on the project.

2.2 Objectives

The main objective of the SLABE project was to enhance the predictive capability of the RFOIL analysis tool, with a focus on a class of profiles increasingly used in modern wind turbine blades for their structural and aerodynamic benefits: flatback airfoils. Specific objectives included:

1. Development and integration of the Double Wake (DW) method into RFOIL: To improve the representation of wake effects behind flatback airfoils and achieve higher accuracy in aerodynamic predictions.
2. To identify and implement further improvements for complex flow conditions, such as the changes in flow shear and the wake length estimation due to the flatback geometry.
3. Provision of baseline and updated versions of RFOIL for consortium partners: To ensure consistent comparison and validation across all participants.
4. Validation of the enhanced RFOIL tool using experimental data from OEM partners: To benchmark improvements against state-of-the-art datasets provided by the consortium.

2.3 Work Plan

2.3.1 WP1: Development of the double wake method (Leading: TNO)

The existing single-wake model in RFOIL was revised to introduce a double-wake approach, specifically aimed at improving the analysis of flatback airfoils. The second wake is released from the point of flow separation, as determined by solving the boundary layer equations within RFOIL.

The solution procedure was updated to account for the presence of the second wake, including the necessary adjustments to the boundary condition to ensure consistency in the governing equations. These modifications were based on established methodologies from the literature and were specifically adapted for RFOIL within the SLABE project.

Development of the double-wake functionality followed an iterative process. The initial phase focused on implementation and preliminary validation using experimental aerofoil data provided by consortium partners. Results were shared with industrial partners for review, and their feedback was incorporated to refine the model. However, while the first implementation did not produce significant changes from baseline, a more advanced solution was proposed but could not be completed due to organisational changes. The final version thus reflects both the technical advancements and the collaborative validation process undertaken during the project.

2.3.2 WP2: Collection of State-of-the-Art Wind Tunnel Experimental Data (Leading: Partners)

The industrial partners contributed aerodynamic datasets obtained from wind tunnel measurements. These datasets were used to develop and validate the modified RFOIL tool. Each partner gathered comprehensive airfoil data, including force coefficients (lift and drag), moment coefficients, across a wide range of operating conditions defined by Reynolds numbers and angle of attack. Some partners also provided pressure distribution, which has allowed for a more in-depth analysis of the phenomenon ongoing.

An operating point was defined as a complete set of aerodynamic polars, covering lift, drag, and moment coefficients, measured over a broad range of angles of attack at a single Reynolds number. Where available, pressure coefficient distributions were included to provide additional insight into flow behavior. Geometric coordinates for each airfoil were also supplied to ensure accurate representation in simulations.

To the extent of what was possible from the measurements available, partners generally provided six operating points for a representative selection of Flatback airfoils with varying thicknesses, defined relative to the foil chord length.

For each airfoil type, two datasets were collected: one for a clean surface, entailing natural transition from a laminar to turbulent boundary layer, and one for tripped conditions, enforcing a turbulent boundary layer from a specific location. Partners shared non-dimensionalised proprietary airfoil geometry data that TNO kept confidential from one partner to the other. The selection of airfoils was based on joint discussions between TNO and the consortium to ensure relevance, accuracy, and robustness for modern blade design applications.

2.3.3 WP3: Validation of the final version (Lead: TNO, Partners)

The validation of the updated RFOIL version was a collaborative effort between TNO and the industrial partners. In the initial phase, TNO used airfoil datasets provided by consortium partners, along with its internal database. This process involved comparing simulation results against experimental data, focusing on key performance indicators such as prediction accuracy and computational efficiency. Following this, TNO prepared and shared a validation report with the consortium, summarizing the outcomes and highlighting areas for improvement.

An executable version of RFOIL incorporating the current DW method was then distributed to all partners for internal testing. Each partner conducted validation using proprietary datasets.

TNO initiated a second development phase to refine, where possible, the initial developments. This second phase was heavily affected by TNO's reorganisation. The changes to improve and have a functioning Double Wake method implemented in RFOIL were left in development and could not reach final product. A final version of the new RFOIL software, including the other improvements made within the project, was delivered. Final validation reports were prepared and shared individually with each partner to maintain confidentiality.

2.3.4 WP4: Project Management (TNO)

WP4 was devoted to coordinating the project, administration, and reporting, and ensuring the technical consistency and convergence towards the main objectives. In particular, the WP aimed to:

- Ensure the strategic and operational management of the project
- Interface with RVO
- Provide financial and contractual management of the consortium.

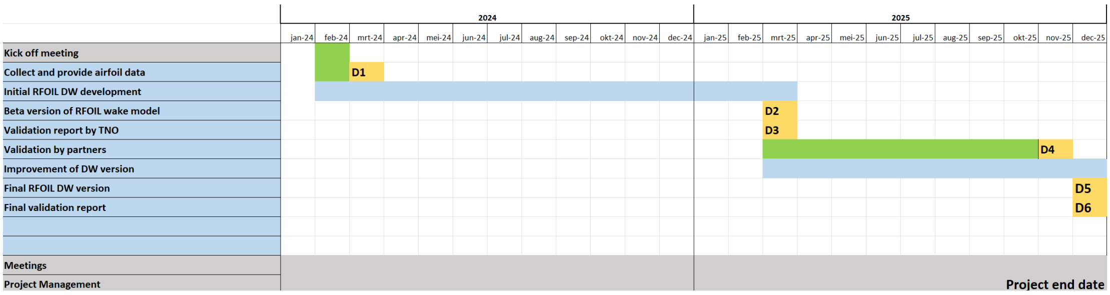

Figure 2.1: Project timeline and deliverables (Di, i=1:6).

3 Results

3.1 Coordination

TNO has been coordinating this project. Ambivalent cooperation and competition between industry partners led to a mixed approach to communication within the project. Common meetings were held regularly for communication and coordination, while bilateral meetings between TNO and single partners were used for the technical result discussions.

Due to delays in the kick-off of the project, there has been a first end-date shift from May 2025 to December 2025. This change had no impact on the timeline and development.

3.2 Improvements for flatback airfoil analysis

This section described the main changes to RFOIL made with the goal of improving RFOIL for modelling flatback airfoils.

3.2.1 Wake modeling

The velocity profile used to derive the closure relations and represent the turbulent boundary layer is [5]

$$\frac{u(\eta)}{u_e} = \sqrt{\frac{C_f}{2}}\frac{1}{0.09}arctan\left[0.09\frac{\rho u_e \eta}{\mu}\sqrt{\frac{C_f}{2}}\right] + \left(1 - \sqrt{\frac{C_f}{2}}\frac{\pi}{0.18}tanh^{1/2}\left[a(\eta/\theta)^b\right]\right) \quad (3.1)$$

where η is the wall normal direction, C_f is the skin friction, u_e is the edge velocity, θ is the momentum thickness and a and b are constants determined by the boundary layer solution. However, this profile is not valid immediately after the airfoil in the wake. Thus, a 'dead air' region is considered where the boundary layer equations are not solved. The shape of the

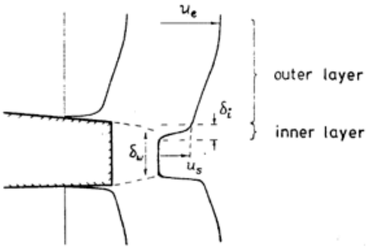

Figure 3.1: Dead air region behind the airfoil [5]

dead air region is modelled by [5]

$$\delta_w = h_{TE}\left[1 + \left(2 + \frac{L_w}{h_{TE}}\frac{d\xi}{dx}\right)\bar{\xi}\right](1-\xi)^2 \quad (3.2)$$

where $\bar{\xi}$ is the non-dimensional distance from the trailing edge and L_w is the length of the dead air region empirically defined as

$$L_w = 2.5h_{TE}. \quad (3.3)$$

This distance is closely related to the length of the recirculation zone behind the trailing edge and is different for flatback airfoils than traditional blunt trailing edge airfoils. To gain further insights, high-fidelity URANS simulations were run for all partner airfoils, and the trailing edge wake length was extracted. Depending on the airfoil, simulations yielded factors of $0.6 \leq \frac{L_w}{h_{TE}} \leq 1.35$. Furthermore, the results suggested that this factor is a function of the airfoil's geometry in terms of airfoil thickness and trailing edge thickness, and of the operational regime in terms of angle of attack and wake characteristics (e.g. fully-separated wake or distinct vortex shedding).

To establish a precise function for the trailing edge wake length, further investigations into the underlying physical phenomena are required. Nonetheless, the simulations demonstrated that the originally implemented value is not suitable for flatback airfoils. Thus, for the current version of RFOIL, this is changed to

$$L_w = h_{TE}. \tag{3.4}$$

3.2.2 Shear stress in the post stall regions

Turbulence modelling within RFOIL is contained in the shear lag equation [6] given by

$$\frac{\partial \left(u_e C_\tau\right)}{\partial x} = \frac{C_\tau u_e}{\delta} K_c \left(C_{\tau,EQ}^{1/2} - C_\tau^{1/2}\right) - C_\tau \frac{\partial u_e}{\partial u}. \tag{3.5}$$

C_τ is the turbulent shear stress and $C_{\tau,EQ}$ is the turbulent shear stress under equilibrium conditions. This equilibrium shear stress is modelled by closure relations. However, the flow over an airfoil is rarely under equilibrium and hence the eq. (3.5) models the deviation of the boundary layer from the equilibrium state. The definition of the different terms can be found in literature [1]. The term K_c is expanded in more detail here. Originally in RFOIL, it is assumed to be $K_c = 5.6$ for attached flows and $K_c = 3.65$ under separated conditions. The variation between the two states is modelled as

$$K_c = 4.65 - 0.95 tanh\left(0.275H - 3.5\right) \tag{3.6}$$

In the current version it is modified to

$$K_c = 0.5\left[(5.6 + 3.65) - (5.6 - 3.65)\, tanh(0.8H - 4.48)\right]. \tag{3.7}$$

The difference of original and updated K_c implementation is shown in Figure 3.2.

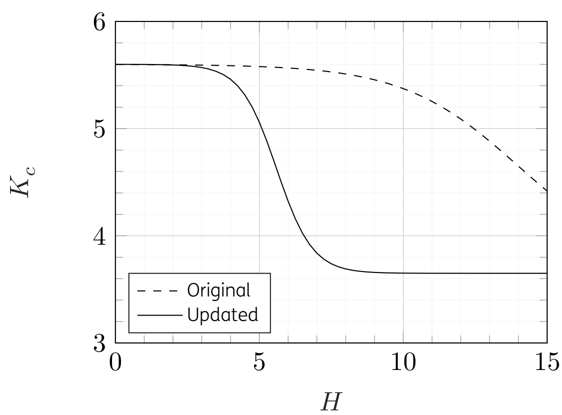

Figure 3.2: Original and updated implementation of the K_c parameter as a function of the shape factor H

3.2.3 Double wake model

The double wake approach is proposed to be an improvement to the inviscid part of the flow. Currently, RFOIL models an 'equivalent inviscid flow' to model the outer flow while accounting for the effect of the boundary layer. The wake region which is important for the boundary layer solution is computed based on the inviscid solution. Downstream of the trailing edge, the inviscid flow 'sees' a viscous flap defined by the dead air region mentioned earlier. While this approach is suitable for attached and mildly separated flows, further improvements are possible for highly separated flows and airfoils with flatback trailing edges.

The double wake algorithm is intended to be such an improvement. In this approach, a second wake is released from the point of flow separation. An initial attempt to implement the double wake solver followed the approached schematically shown in fig. 3.3. In this implementation, the solution from the double wake was fed back into the solution routine of RFOIL. Contrary to initial intuition, this did not lead to results varying from the baseline RFOIL implementation. Upon investigation, it was found that this approach merely changed the starting condition of solution process but failed to change its convergence behaviour.

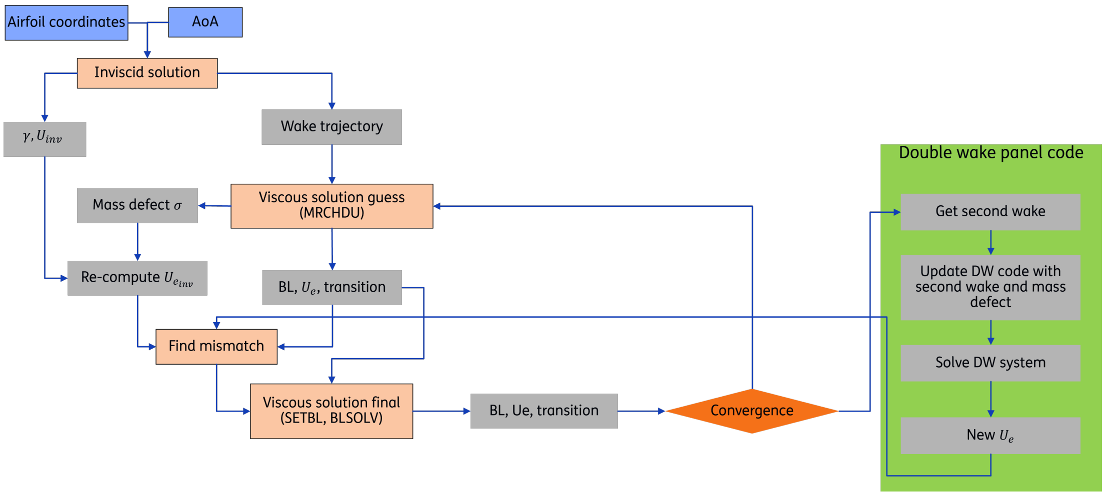

Figure 3.3: RFOIL algorithm extended by double wake method

In a second attempt, a more advanced solution process was targeted, see fig. 3.4. In this attempt, the coefficient matrices would have been extended to include both wakes. Unfortunately, the reorganisation at TNO led to the lead developer being let go and the implementation of this second approach could not be completed.

3.2.4 Results for the public LI30FB airfoil

To facilitate the communication of results with all partners present, simulations were run on the publicly available LI30FB flatback airfoil. Its geometry is shown in fig. 3.5.

For this airfoil, experimental data are available in the literature [7]. Next to the experimental data, simulation results from RFOIL.v3 and from the version developed in the SLABE project (here denoted v4b) are shown. Additionally, XFOIL, the tool on which RFOIL is originally based, was run, too. The experimental data was obtained in a wind tunnel with reported turbulence intensity of $TI \leq 0.2\%$. Using Mack's relation [8]

$$-8.43 - 2.4\log\left(\frac{TI}{100}\right) , \tag{3.8}$$

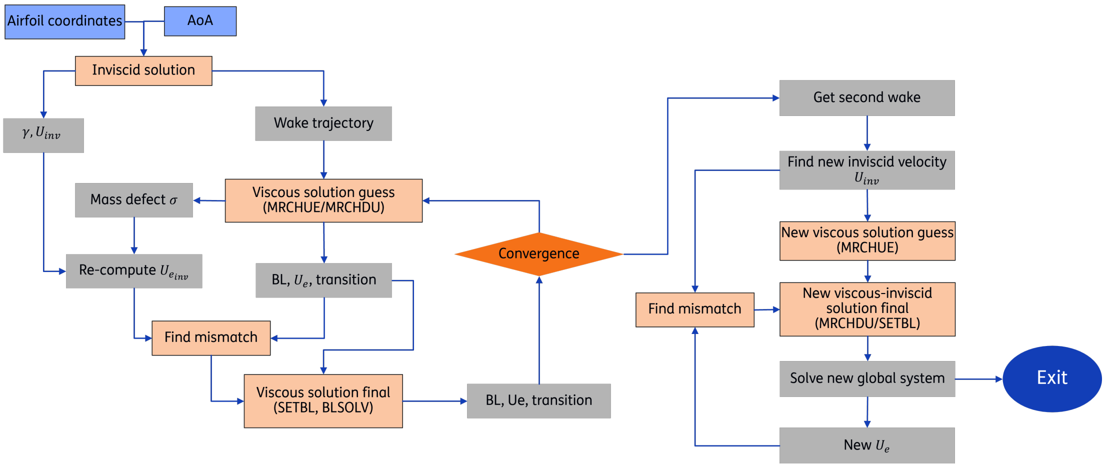

Figure 3.4: RFOIL algorithm extended by double wake method

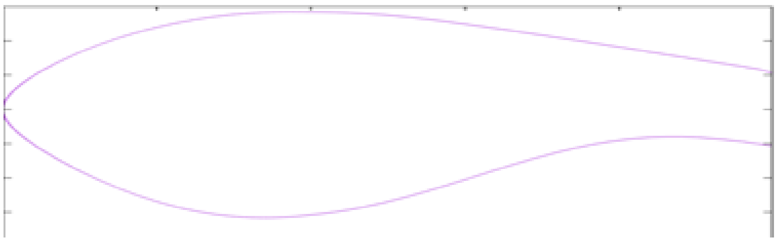

Figure 3.5: Geometry of the publicly available LI30FB flatback airfoil

TI can be related to the critical amplification factor N_{crit} which influences the transition behaviour from laminar to turbulent flow. The TI of the experiments yields $N \approx 6$. Next to that, fully turbulent (FT) RFOIL simulations were run for comparison.

The measured and simulated lift and drag polars are shown in fig. 3.6. A particular feature of this flatback airfoil is the dip in drag around an angle of attack of 10°. The newly developed RFOIL version shows signs of being able to capture this dip better than previous implementations.

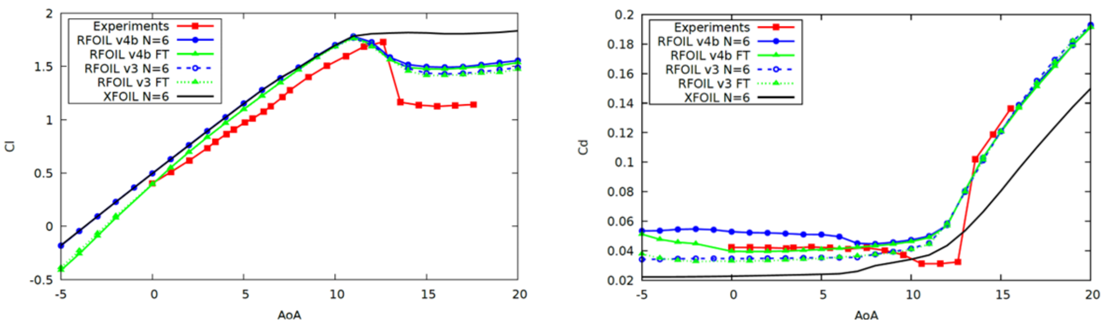

Figure 3.6: Comparison of numerical and experimental polars of the publicly available LI30FB flatback airfoil

3.3 Dissemination

The core of the work relied on sensitive information making the dissemination of the development not a priority in this project, apart from the planned technical confidential and public deliverables, including the RFOIL code update. Furthermore, the mentioned reorganisation has halted any efforts in un-planned but valued dissemination in public papers and conferences.

4 Conclusions and Recommendations

The SLABE project, although in a limited way, advanced the aerodynamic simulation capabilities of RFOIL for flatback airfoils. Three primary development lines were pursued: implementation of a double wake method, adjustments to closure relations, and improved treatment of the trailing edge wake region for flatback airfoils.

An updated version of RFOIL was developed incorporating changes aimed at improving flatback airfoil modeling. The modified trailing edge wake length treatment and updated shear stress formulation have been shown to yield successful improvements on a selection of airfoils and overall potential to capture the observed flow behavior behind blunt trailing edges. Validation against the public LI30FB airfoil was used to demonstrate the improvement. In particular, the updated RFOIL version more accurately captures the characteristic drag dip, showing closer agreement with experimental data compared to both RFOIL v3 and XFOIL across the operational envelope. The latest version of RFOIL was tested during development and validated using proprietary datasets from consortium partners, covering flatback geometries with trailing edge thicknesses ranging from 20% to over 50% of chord length across multiple Reynolds numbers.

The project framework established through the TKI Wind op Zee program proved effective for industry collaboration. By bringing together competing OEMs, including Vestas, Nordex, Suzlon, GE Vernova/LM Wind Power and Siemens Gamesa Renewable Energies, the consortium successfully advanced common knowledge while maintaining confidentiality of proprietary data. Monthly coordination meetings and bilateral technical discussions balanced the needs for open collaboration and competitive protection.

The project faced significant challenges due to organizational restructuring at TNO Wind Energy, which resulted in the departure of the lead developer midway through execution. Consequently, the advanced double wake implementation, while well-structured and positioned for future completion, was not finalized within the project timeline. An initial double wake implementation has not produced significant deviations from baseline; a new and more advanced solution methodology remains partially complete.

Despite these setbacks, the project outcomes provide knowledge and a foundation for continued development. The code framework for the double wake method is in good condition for completion in future work. Industrial partners expressed continued interest in RFOIL enhancement, confirming the tool's ongoing relevance to blade design workflows.

TNO Wind Energy also remains committed to maintaining and advancing RFOIL through collaborative partnerships with commercial entities and research institutions. Priority areas for future development include completing the double wake implementation using the advanced solution framework developed in SLABE, potentially through academic collaboration as well as continue the research of developments beyond flatback airfoils to address other wind energy applications, such as leading edge erosion, where RFOIL's capabilities can be enhanced.

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