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Quasi-simultaneous interaction for prediction of aerodynamic flow over wind turbine blades

H.A. Bijleveld

A.E.P. Veldman (Rijksuniversiteit Groningen)

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Quasi-simultaneous interaction for prediction of aerodynamic flow over wind turbine blades

H.A. Bijleveld[1), A.E.P. Veldman[2)
[1) Energy research Centre of the Netherlands; University of Groningen
[2) University of Groningen
The Netherlands

ABSTRACT
A numerical simulation method for an accurate and fast prediction of the aerodynamic behaviour of wind turbine blades (RotorFlow) is currently under development. In this method, the total flow field around a blade is split into an inviscid external flow – to be solved with a potential flow solver – and a viscous boundary layer where integral boundary-layer equations are used. At the edge of the flow domains, both flows are coupled via an interaction formulation. The quasi-simultaneous interaction law will be used which has proven to be successful in 2D. A formulation for the 3D flow over rotating blades is now being developed.

KEYWORDS
Wind turbine blades, boundary layer, viscous-inviscid interaction, quasi-simultaneous coupling

1 Introduction

The current trend in wind turbine design is toward larger rotor blades. This brings challenges for the structural design as more and more material is involved and the blades become more flexible which is a challenge from a (aero)dynamic viewpoint. Safety factors – to compensate for uncertainties during design - should be as low as possible to avoid the use of unnecessary material. Besides, for optimisation purposes, design methods need to be fast.
Therefore, an accurate and fast prediction of the aerodynamic behaviour of a blade is needed. Current methods that are fast in the prediction use crude models like BEM (Blade Element Momentum). For an accurate prediction of the flow, full Navier-Stokes equations need to be solved which requires huge computational efforts.

2 Rotorflow

A method that is low in computational effort, but with a more detailed solution than the BEM methods is pursued in the project RotorFlow of ECN. In this method, the whole flow field is split into two flow domains: an inviscid external domain and a small viscous boundary layer at the surface of the blade. An interaction between the domains ensures a continuous solution between the two domains.

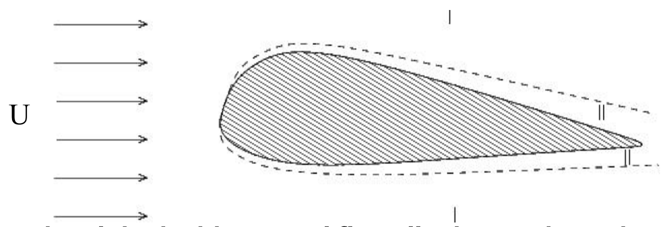

Figure 1: The flow domains. I: inviscid external flow; II: viscous boundary layer, dashed line: viscous-inviscid interaction, U: the undisturbed free-stream velocity (=wind).

Figure 1 shows the flow domain over an airfoil. The dashed line indicates the edge between the two domains. This is where a viscous-inviscid interaction is present. Region I is the inviscid external flow that can be calculated with a potential flow panel method. Region II is the viscous boundary layer where the quantities of the boundary layer are obtained with an integral boundary-layer calculation. The flow variables that are of interest at the edge of the two domains are the velocity vector ($\mathbf{u_e} = (u_e,v_e,w_e)^T$) and the boundary-layer displacement thickness: δ^* (see Figure 2).

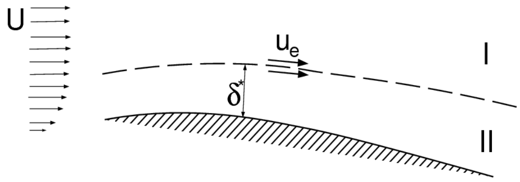

Figure 2: Variables u_e and δ^* in the flow domains.

3 Viscous-inviscid Interaction

The viscous-inviscid interaction (VII) can be performed in several ways. Four main methods can be distinguished. Figure 3 shows them graphically and they are discussed in detail in the following section.

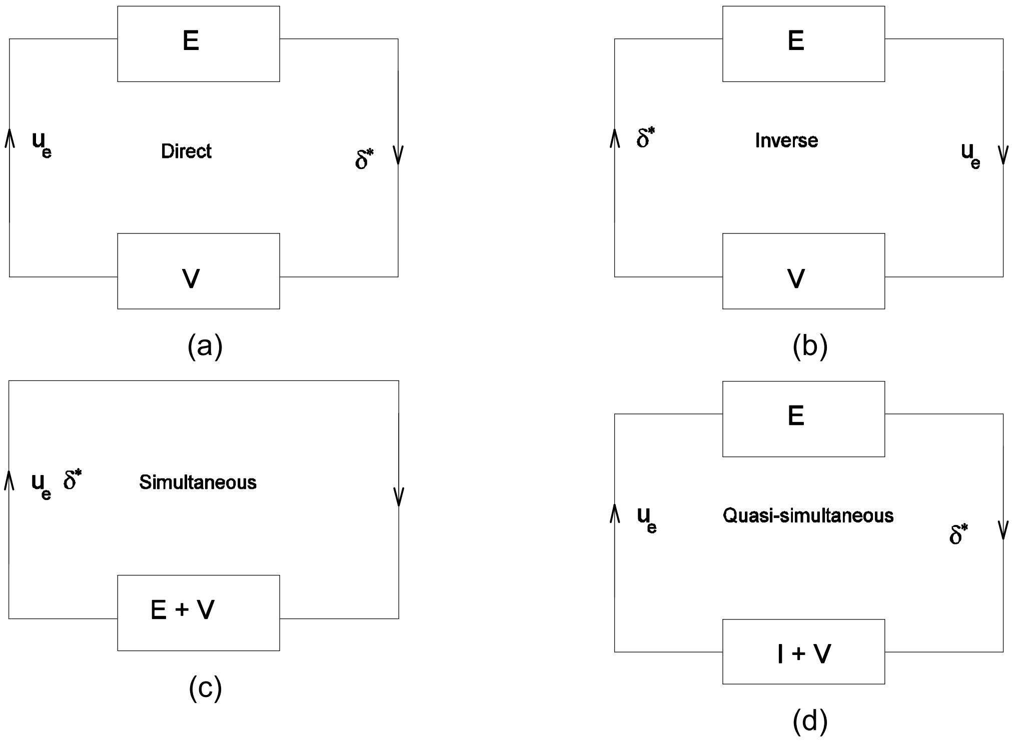

Figure 3: Schematic of four main interaction methods: E = external flow equations, V = boundary-layer equations, I = interaction law:

$$\begin{cases} u_e = E[\delta^*] \\ u_e = V[\delta^*] \end{cases}$$

a) direct method b) inverse method c) simultaneous method d) quasi-simultaneous method.

3.1 Main groups of interaction methods

In the direct method (see Figure 3a), the external flow prescribes the velocity on the boundary layer. The boundary layer gives the displacement thickness to the external flow. The method is unable to handle separated flows.
In the inverse method (Figure 3b), the boundary layer imposes the velocity onto the external flow. It can handle separated flows, but converges slow.
Simultaneously solving the external and boundary-layer flow converges faster, but is complex in software terms and lacks flexibility in flow modelling.
The complicated software of the simultaneous method is avoided by solving the boundary layer together with an approximated external flow and subsequently calculating the complete external flow. The approximation is given by an interaction law. This idea was introduced by Veldman [1] and is drawn in Figure 3d. It turns out to be a powerful method that is comparable to the direct method but able to calculate separated flows.

3.2 Quasi-simultaneous interaction method

The main challenge of the quasi-simultaneous interaction method is the formulation of the interaction law. Thin-airfoil theory gives a useful approximation of the external flow and is therefore used as basis for the interaction law.
The complete flow field is computed by iteratively solving the external flow and the boundary layer with the interaction law, see Figure 3d. Mathematically, this can be written as:

$$(I-E)\delta^{*(n)} = (I-V)\delta^{*(n-1)}. \tag{1}$$

In this formula, I is the interaction law; V are the viscous boundary-layer equations, E represents the external flow equations and n the iteration number. If convergence is achieved, then:

$$(E-V)\delta^{*} = 0, \tag{2}$$

which shows that the formulation of the interaction law is not influencing the final solution.
In 2D applications, the interaction law with only non-zero terms on the diagonal of I turns out to be the most robust [2]. Figure 4 shows a lift polar for the NACA0012 airfoil. It shows that the calculations performed with the viscous method following the quasi-simultaneous approach agree very well with the experimental data even in the region around maximum lift. The calculations turn out to be robust and take only seconds on an average PC. Due to the good results in the stall region, a wide variety of wind scenarios on wind turbine blades should be possible to be analysed with ROTORFLOW.

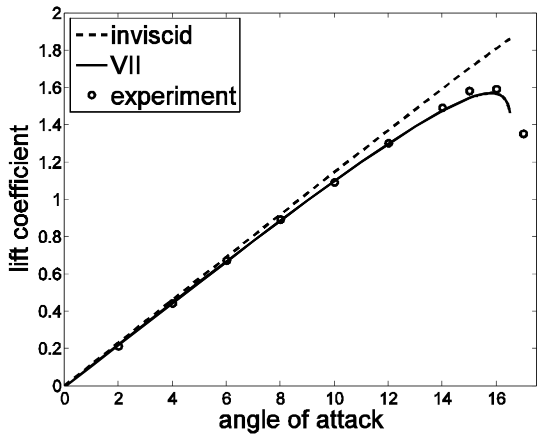

Figure 4: Lift polar for NACA0012 airfoil: viscous-inviscid (VII) calculation versus experiment [3].

Applications of a three-dimensional interaction law for quasi-simultaneous interaction methods hardly exist. This PhD project focuses on the formulation and derivation of a 3D interaction law to be used for the simulation of unsteady aerodynamic flow over wind turbine blades.

4 Conclusion

For a fast and accurate aerodynamic design code, where the flow field is split into a viscous and inviscid part, a three-dimensional quasi-simultaneous interaction method will be developed for use in applications for wind turbine blades. Results in 2D applications suggest this to be an accurate and robust interaction method.

BIBLIOGRAPHY

[1] Veldman, A.E.P.: New, quasi-simultaneous method to calculate interacting boundary layers, AIAA J. 19:79-85, 1981

[2] Coenen, E.G.M.: Viscous-Inviscid Interaction with the Quasi-Simultaneous Method for 2D and 3D Aerodynamic Flow, PhD thesis, Rijksuniversiteit Groningen, the Netherlands, 2001

[3] Veldman, A.E.P.: Quasi-Simultaneous Viscous-Inviscid Interaction for Transonic Airfoil Flow, AIAA-2005-4801, 4th AIAA Theoretical Fluid Mechanics Meeting Toronto, June 6-9, 2005