https://lib.uliege.be https://matheo.uliege.be

Master thesis and internship[BR]- Master's thesis : A Wall Model for LES of Flows with Laminar-Turbulent Transition[BR]- Integration Internship : TU Delft

Auteur : Dujardin, Nicolas
Promoteur(s) : Terrapon, Vincent
Faculté : Faculté des Sciences appliquées
Diplôme : Master en ingénieur civil en aérospatiale, à finalité spécialisée en "aerospace engineering"
Année académique : 2022-2023
URI/URL : http://hdl.handle.net/2268.2/18179

Avertissement à l'attention des usagers :

Tous les documents placés en accès ouvert sur le site le site MatheO sont protégés par le droit d'auteur. Conformément aux principes énoncés par la "Budapest Open Access Initiative"(BOAI, 2002), l'utilisateur du site peut lire, télécharger, copier, transmettre, imprimer, chercher ou faire un lien vers le texte intégral de ces documents, les disséquer pour les indexer, s'en servir de données pour un logiciel, ou s'en servir à toute autre fin légale (ou prévue par la réglementation relative au droit d'auteur). Toute utilisation du document à des fins commerciales est strictement interdite.

Par ailleurs, l'utilisateur s'engage à respecter les droits moraux de l'auteur, principalement le droit à l'intégrité de l'oeuvre et le droit de paternité et ce dans toute utilisation que l'utilisateur entreprend. Ainsi, à titre d'exemple, lorsqu'il reproduira un document par extrait ou dans son intégralité, l'utilisateur citera de manière complète les sources telles que mentionnées ci-dessus. Toute utilisation non explicitement autorisée ci-avant (telle que par exemple, la modification du document ou son résumé) nécessite l'autorisation préalable et expresse des auteurs ou de leurs ayants droit.

A Wall Model for LES of Flows with Laminar-Turbulent Transition

University of Liège
Faculty of applied Sciences
Academic year 2022-2023

Author:	Nicolas Dujardin	
Promoter:	Prof. Vincent E. Terrapon	Uliège
Supervisor:	Prof. Stefan Hickel	TU Delft

Abstract

Large Eddy Simulations (LES) offer a better reliability than the Reynolds-Averaged Navier-Stokes method and a more acceptable computational cost compared to Direct Numerical Simulations. Nevertheless, with such an approach, wall-bounded flows at high Reynolds numbers require an excessively fine mesh resolution to fully resolve the energetic turbulent structures within the inner boundary layer. Consequently, the related computational cost is a major obstacle for most practical engineering settings. To overcome this, Wall-Modeled Large Eddy Simulations (WMLES) estimate instead of resolve the effect of the inner layer. Considering the wall-stress modeling approach, this is achieved by providing the wall-shear stress as a Neumann boundary condition and enforcing the impermeability instead of imposing a no-slip condition over the wall. In this context, a wall-stress model is built for incompressible flows including laminar-turbulent transition. As a first step, a laminar wall model (LWM) is established by assuming a self-similar boundary layer based on the Falkner-Skan equation. The model is able to provide a friction estimate from the knowledge of the pressure at the wall vicinity. A validation with respect to wall-resolved solutions is then carried out by considering a flat plate and the Hiemenz flow. The robustness and accuracy of the LWM are demonstrated in both cases, except near the leading edge of the flat plate where the self-similarity assumption is not appropriate.

Then, a method for calculating distances on irregular triangular meshes is developed in order to apply the LWM to curved surfaces. The resulting algorithm provides the shortest distance over the surface with respect to an imposed set of stagnation points. A succession of convergence studies for different test cases demonstrates that the process leads to a distance field with a sufficiently good accuracy and smoothness for wall-modeling applications.

A hybrid wall model (HWM) is finally built by combining the LWM with a turbulent wall model based on the general wall function. In order to validate it, different flows over an extruded wing are considered: the NACA0012 with ($Re = 10.25 \cdot 10^6$; AoA $= 0°$) and the A-airfoil with ($Re = 3.1 \cdot 10^6$; AoA $= 3.4°$) and ($Re = 2.1 \cdot 10^6$; AoA $= 13.3°$). The HWM is first applied by hard-coding the transition between the two wall functions. The resulting wall-shear stress shows a good match with the empirical data for fully attached flows. Lastly, a sensor measuring the turbulent kinetic energy is used at each point of the surface to automatically determine the type of regime and impose the wall treatment accordingly. As long as the imposed sensor threshold is suitable and the mesh resolution sufficiently fine, the sensor is able to predict a transition corresponding relatively well with the experiment. However, the results show that these sensor parameters are case dependent.

Representative Illustrations

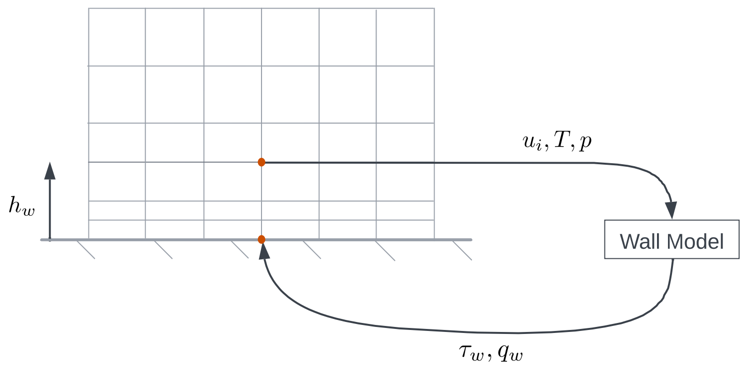


Figure 1: Schematic representation of the wall-stress modeling. Adapted from Larsson et al. [1].

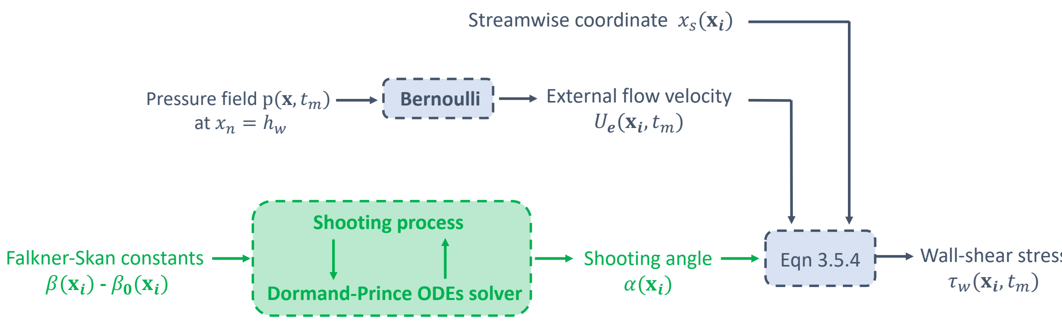
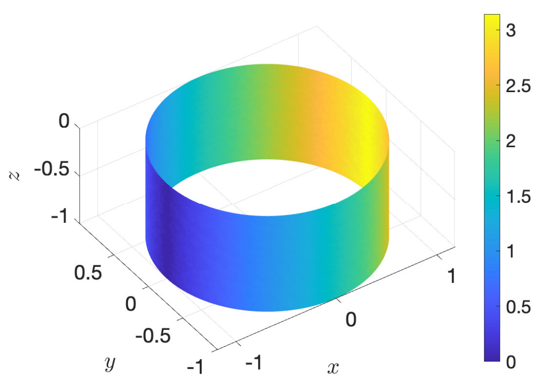
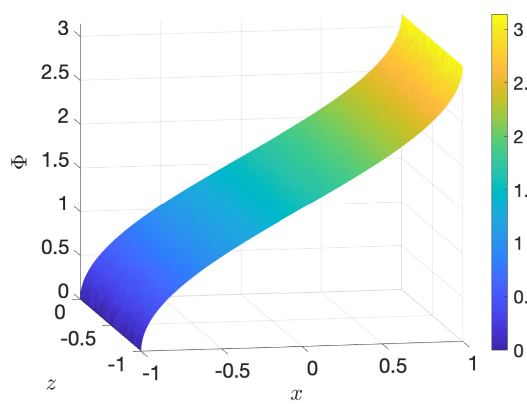


Figure 2: Schematic representation of the laminar wall model (LWM) considering the wall point $\mathbf{x}_i$ at the m^{th} time step (blue part) and the related pre-processing (green part).



(a) Final Φ field with the geometry in 3D.



(b) Final Φ field with the geometry projected in a xz-plane $\forall y \geq 0$.

Figure 3: Reinitialization process applied to a cylinder centered in $(x,\, y) = \mathbf{0}$ and with a stagnation line imposed in $(x,\, y) = (-1, 0)$.

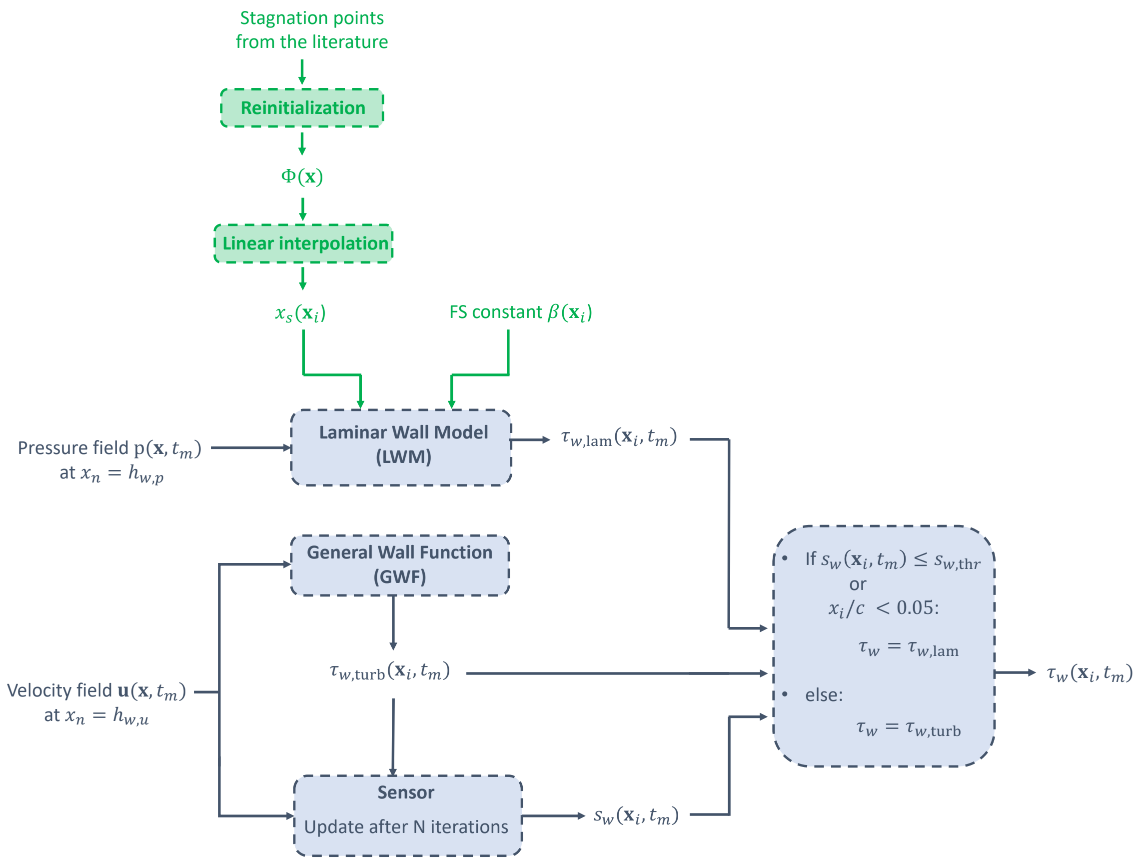
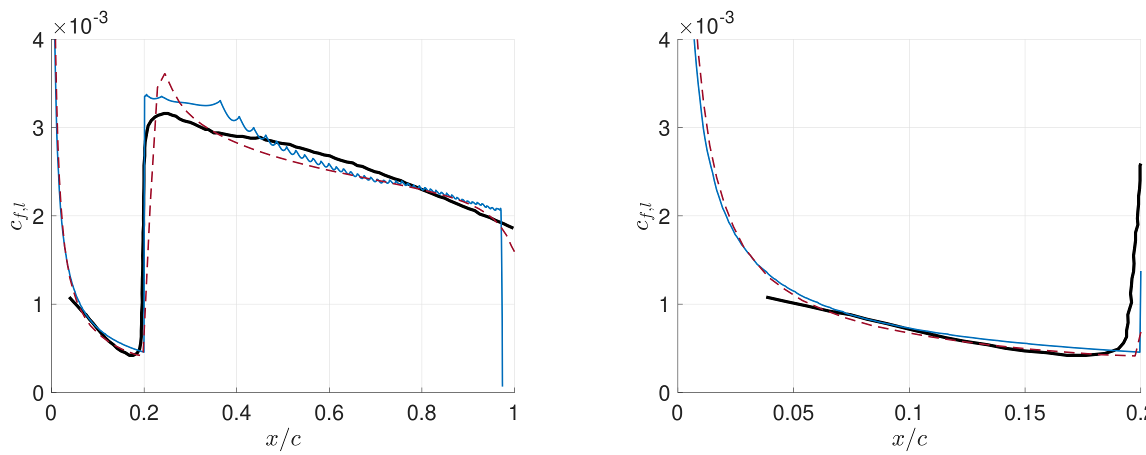


Figure 4: Hybrid wall model (HWM) with transition detection. Schematic representation of the model considering the wall point $\mathbf{x}_i$ at the m^{th} time step (blue part) and the related pre-processing (green part).



(a) Local skin friction coefficient.

(b) Zoom of $c_{f,l}$ in the laminar part.

Figure 5: NACA0012 with $Re = 10.25 \cdot 10^6$ and AoA $= 0°$. Local skin friction from the HWM with hard-coded transition (solid line, blue), from *X-foil* [2] with $N_{\mathrm{crit}} = 4$ (dashed line, red) and from the experiment [3] (solid line, black).

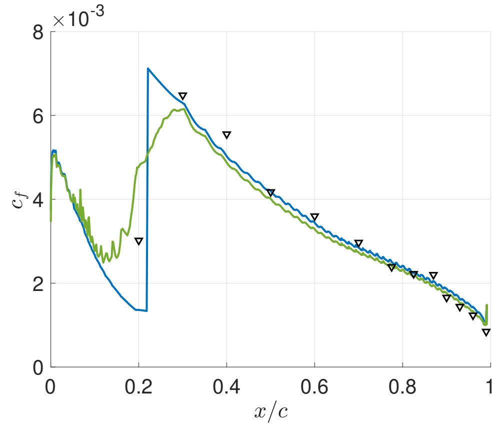


Figure 6: A-airfoil with $Re = 3.1 \cdot 10^6$ and AoA $= 3.4°$. Skin friction from the HWM with transition detection (green line), from the HWM with hard-coded transition (blue line) and from the F1 tunnel [4] (black triangles).

References

[1] U.J. Larsson, S. Kawai, J. Bodart, and I. Bermejo-Moreno. "Large eddy simulation with modeled wall-stress: recent progress and future directions". In: *Mechanical Engineering Reviews* 3.1 (2015).

[2] *Xfoil documentation, Description.* `https://web.mit.edu/drela/Public/web/xfoil/xfoil_doc.txt`. Accessed: 2023-04-04.

[3] J.V. Becker. "Boundary-Layer Transition on the NACA 0012 and 23012 Airfoils in the 8-Foot High-Speed Wind Tunnel". In: *National Advisory Committee for Aeronautics, Special Report* 137 (1940).

[4] W. Haase, E. Chaput, E. Elsholz, M. Leschziner, and U. Miiller. "ECARP - European Compuational Aerodynamics Research Projects: Validation of CFD-codes and Assessment of Turbulence Models". In: *Vieweg Verlag* 58 (1997).