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AIRFOIL TRANSITION TO TURBULENCE PREDICTION USING A SIMPLIFIED ENVELOPE METHOD

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Abstract. *The inclusion of transition to turbulence effects in numerical simulations has a direct influence on the ability of computational tools to correctly reproduce aerodynamic coefficients. While high-fidelity tools accounting for transition to turbulence are today largely used in airplane design during both the conceptual and preliminary phases, they still represent high computational costs. In order to better explore the design space in a reasonable time frame, designers also employ lower fidelity approaches in the early design phase. We investigate the transition to turbulence capabilities as implemented in Xfoil, which is a panel method code that includes viscous effects through boundary layer estimations. Within Xfoil, the transition to turbulence effects are included by means of the so-called approximate envelope method, which we also describe in this paper. We compare the results obtained with this lower fidelity tool with the ones obtained by using the high-fidelity, nonparallel and nonlocal Parabolized Stability Equations (PSE) technique. Our results indicate that Xfoil predicts the expected transition front upstream movement trend when the freestream Reynolds number and turbulence intensity are increased, even though some offset is observed when comparing these numerical results with the ones obtained with higher-fidelity prediction tools. According to our numerical results, Xfoil is able to predict lift and drag coefficients for airfoils in transitional flow within levels of accuracy compatible with early-stage design requirements.*

Keywords: *Transition to turbulence, flow stability analysis, approximate envelope method, Xfoil*

1. Introduction

The modeling and prediction of transitional flows has received considerable attention from engineers and researchers in the last decades. Understanding the nature of the fluid flow is essential in the prediction of drag, lift and, therefore, of the overall efficiency of an airfoil. In this sense, previous publications addressed high-fidelity transitional flow simulations over airfoils and wings (Halila *et al.*, 2016b, 2018) as well as over high-lift devices (Halila *et al.*, 2016a, 2019a). These investigations used Reynolds-Averaged Navier–Stokes (RANS) models that account for transition effects by adding new transition transport equations to an underlying turbulence model. Transition turbulence effects were also included in high-fidelity, gradient-based aerodynamic shape optimization (Halila *et al.*, 2020; Shi *et al.*, 2020). In the present paper, we extend previous efforts by assessing the capability of Xfoil (M. Drela, 2001) to predict the transition front and the aerodynamic coefficients of airfoils in subsonic flow in which transition to turbulence takes place. This contribution aims at providing a better understanding on how Xfoil can be used to predict free transition over airfoils in early phases of conceptual design.

There are different physical mechanisms that can trigger transition to turbulence. The amplification of Tollmien-Schlichting (TS) waves is one of the most common transition mechanisms in flows over unswept wings. Laminar Separation Bubbles (LSB) are also a common mechanism for wings and airfoils at higher angles of attack. Crossflow (CF) vortices tend to cause turbulent flow close to the leading edge of swept wings.

Engineers and scientists developed computational methods for modeling transition to turbulence so that their effects can be predicted and investigated. Among the high-fidelity tools to predict transition to turbulence are the so-called flow stability tools. Some examples are the Linear Stability Theory (LST) and the Parabolized Stability Equations (PSE). A review of modal stability theory can be found in the literature (Juniper *et al.*, 2014). More recently, adapted RANS (Reynolds–Averaged Navier–Stokes) that are capable of predicting transition to turbulence were also introduced. Some

examples are the $\gamma - Re_\theta$ model from Langtry and Menter (Langtry and Menter, 2009; Langtry *et al.*, 2015) and the Amplification Transport Factor (AFT) model from Coder and Maughmer (Coder and Maughmer, 2014; Coder, 2019). Although the aforementioned methods for transition prediction include high-fidelity effects, they require considerable computational resources and, therefore, are time consuming. It is our understanding that, at early design phases, low-fidelity tools should be combined to high-fidelity ones to allow the designer to better explore the design space in a reasonable time scale when many different configurations need to be studied.

One way of simplifying computation complexity in the early stages of development is to use simpler methods of flow modeling, such as panel methods (Hess and Smith, 1964). Naturally, the assumptions behind simplified methods make them unable to perform well in some situations. For instance, it is known that linear aerodynamic tools, such as panel and vortex methods, are not able to account for viscous effects as flow separation. It is possible, however, to improve the prediction capabilities of these methods by coupling their original inviscid flow calculations to boundary layer corrections in the method referred to as zonal approach (Drela and Giles, 1987b).

The present paper discusses the degree to which Xfoil, a panel method, open source software for airfoil analysis and design, can properly evaluate transition caused by TS wave amplification. We compare the results from Xfoil with data generated using the Parabolized Stability Equations (PSE) (Bertolotti *et al.*, 1992) and experimental data. The PSE approach represents the physics of the flow to a high degree of fidelity, since it can capture relevant information like boundary layer flow history and nonparallel effects. The formulation and description of the PSE technique, as well as its coupling to an adaptive RANS solver, can be found in recent publications (Halila *et al.*, 2019b, 2021).

2. The Approximate Envelope Method

One useful quantity in transition to turbulence estimation is the the amplification factor, N . For a single wave, the N -factor is given by

$$N = \ln \left(\frac{A}{A_0} \right) = \int \sigma_E(x) dx, \quad (1)$$

where A_0 is the wave amplitude at the first neutral stability point and σ_E is the energy-based growth rate (Halila *et al.*, 2019b). The transition location can be determined based on an e^N method, in which a critical, threshold value for N is used. Typically, this value comes from wind tunnel or flight test, and can also be determined through empirical correlations and is here referred to as N_{crit} . The N -factor calculation is performed for a set of TS waves, and the envelope of maximum N at each airfoil station is then compared to the threshold value. The position in which the N -envelope reaches N_{crit} is set as the transition onset point.

Drela and Giles (Drela and Giles, 1987b) propose that the N -envelope can be reproduced by a linear approximation. This idea leads to the concept of the approximate N -factor, \tilde{n} , which is seen as a surrogate for the real N -factor,

$$\tilde{n} = \frac{d\tilde{n}}{dRe_\theta} [Re_\theta - Re_{\theta,np}(H_k)], \quad (2)$$

where Re_θ is the Reynolds number based on the momentum thickness, θ , and the subscript np indicates the neutral point location. The momentum thickness Reynolds number at the neutral point location, $Re_{\theta,np}$, is a function of the boundary layer shape factor, H_k , through an algebraic relation available in the literature (Drela and Giles, 1987b). We recall that the shape factor is defined as $H_k = \delta^*/\theta$, where δ^* is the displacement thickness and θ is the momentum thickness for the boundary layer. The slope for the straight line suggested for \tilde{n} in eq. 2, $d\tilde{n}/dRe_\theta$, is also only dependent on the shape factor according to an algebraic relation shown in the literature (Drela and Giles, 1987b). This means that we can estimate the transition onset based only on the knowledge of boundary layer integral quantities. The simplified e^N method only corresponds to the complete e^N approach for constant $H_k(x)$ (M. Drela, 2001).

For TS waves, Mack's correlation (Mack, 1977) can be used to determine N_{crit} as a function of the environment turbulence intensity, Tu ,

$$N_{crit} = -8.43 - 2.4 \ln(Tu). \quad (3)$$

We further observe that Mack's correlation is valid for turbulence levels between 0.1% and 1%. The use of this correlation allows the inclusion of the environmental turbulence spectrum in the numerical investigations.

3. The Xfoil Panel Method Code

Xfoil was developed by Mark Drela (M. Drela, 2001) using a fully coupled viscous/inviscid interaction method (Drela and Giles, 1987b). The code has been improved over the years until it reached its current state, and no further development is planned. The code is open source and is available online.

The numerical approaches used in Xfoil are mainly the same as in the ISES software (Drela and Giles, 1987a). A two-equation lagged dissipation integral boundary layer formulation is used. The potential flow is used to calculate the

viscous boundary layer via a wall transpiration method, which allows a proper definition of limited separation regions. It uses high-order panel methods for increased computational speed, being able to solve the flow field for an airfoil in a few seconds.

4. Impact of Turbulence Intensity on Transition Front Location

A first step to evaluate the transition prediction capability of Xfoil is to examine whether the transition front position varies with the freestream turbulence level, subscribing to the real physics. Higher turbulence levels should cause the transition front to move upstream. In order to avoid transition triggered by laminar separation bubbles, we use a zero angle of attack for the results in this section. Since Xfoil does not take turbulence level as a direct input, we use Mack's correlation, represented by Eq. 3, to determine the N_{crit} value that should be used as an input to Xfoil.

For this analysis we use the Aérospatiale A and NACA 0012 airfoils. The former was designed at the Aérospatiale in 1986, in France, and has been tested on a wind tunnel at the Office National d'Études et Recherches Aéropatiales (ON-ERA). The NACA 0012 airfoil was developed in the decade of 1930 by the National Advisory Committee for Aeronautics (NACA), and was extensively experimented with since then.

The results obtained for the NACA 0012 and the Aérospatiale A airfoils are presented in Fig. 1. We perform simulations with freestream turbulence intensities ranging from 0.1% to 1.0%. We observe that the transition front movement toward the leading edge with increasing freestream turbulence intensities is correctly predicted by Xfoil.

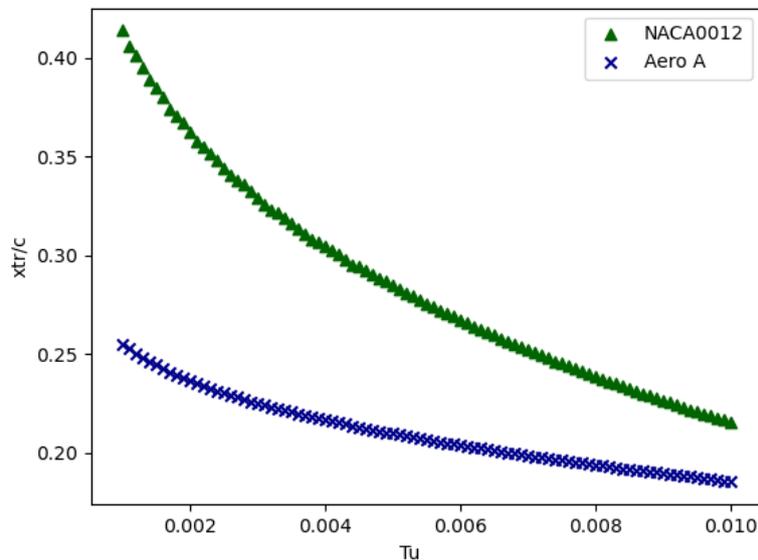


Figure 1. Transition front location for varying freestream turbulence intensities as predicted by Xfoil.

By inspecting Fig. 1, we see that transition fronts for the Aérospatiale A airfoil occurs much closer to the leading edge in comparison to the NACA 0012 airfoil for all of the freestream turbulence intensities considered here. This is due to the pressure distribution over the latter, in which adverse pressure gradients take place closer to the leading edge, causing premature TS wave amplification. One thing to note is that, even though it cannot be visually verified in the figure due to the density of data points, there are some missing points on the Aérospatiale A airfoil curve in Fig. 1. Even though a considerably fine mesh was used for this simulation, Xfoil did not converge for the turbulence levels of 0.14%, 0.18%, 0.48%, 0.53%, and 0.59%. This aspect is currently under investigation.

5. Reynolds number Effects on Transition Front Location

For a given turbulence level, it is also relevant to investigate how the transition position is affected by varying the chord-based Reynolds number. In this case, the results are evaluated by comparing the data extracted from Xfoil with the results presented in a previous study using the PSE approach (Halila *et al.*, 2019b). For this investigation, we perform simulations considering the NLF(1)-0416 and NACA 0012 airfoils.

5.1 NACA 0012 Airfoil

For the NACA 0012 airfoil we use an N_{crit} of 8.14, which corresponds to a turbulence level of 0.1%. The Reynolds number is increased from 1 million to 15 million, as shown in Fig. 2. The angle of attack used was, again, 0 degrees to avoid transition triggered by laminar separation bubbles.

The results from the Xfoil simulations are compared against the PSE-generated data (Halila *et al.*, 2019b). We can

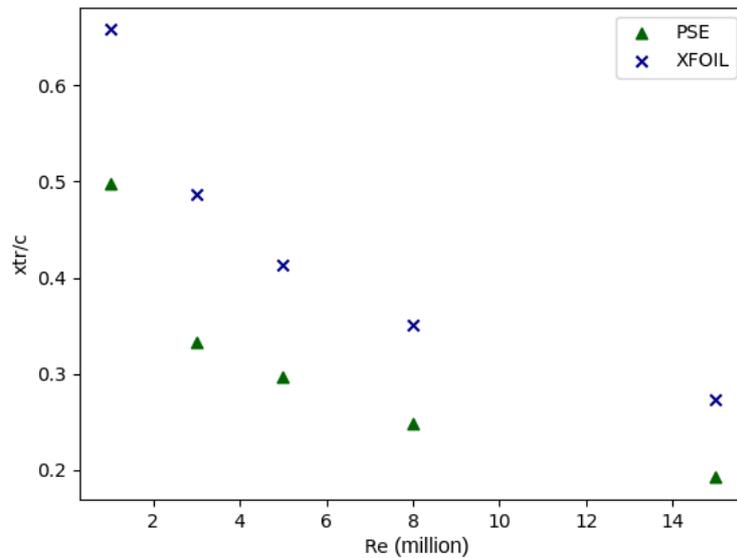


Figure 2. Transition front location for varying Reynolds number as predicted by Xfoil for the NACA 0012 airfoil.

see that Xfoil is able to correctly predict the position of transition trend, indicating a transition front that moves upstream with increasing Reynolds number, but it is not able to predict the same transition positions as the ones obtained by the higher-fidelity approach. These differences in transition location can be understood by observing the boundary layer shape factor distributions, as obtained by Xfoil and by a boundary layer solver for the NACA 0012 and NLF(1)-0416 airfoils, as shown in Fig. 3. The boundary layer shape factor, which is the major variable in the approximate N-factor definition, depicted in Eq. 2, presents differences between the Xfoil and boundary layer solver computations around the transition onset points. These differences are likely causing the transition front mismatches reported above.

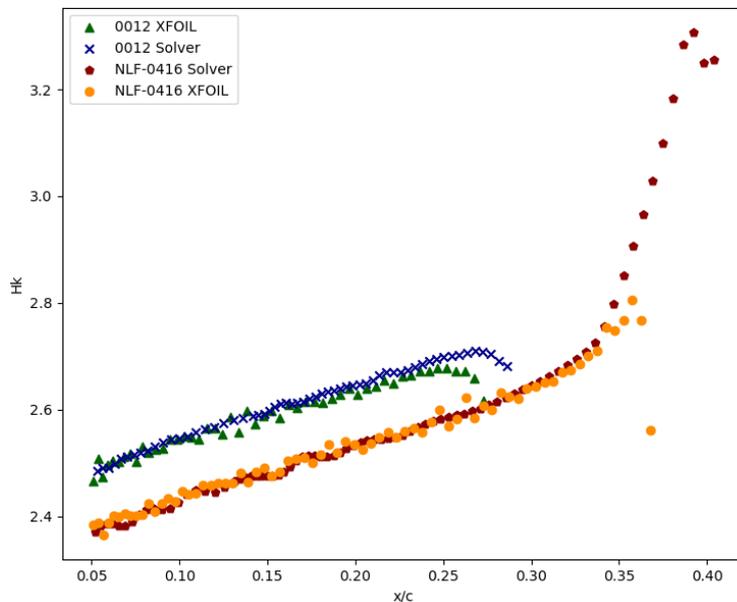


Figure 3. Boundary layer shape factor distributions as computed by Xfoil and a boundary layer solver for the NACA 0012 and NLF(1)-0416 airfoils at a zero-degree angle of attack.

5.2 NLF(1)-0416 Airfoil

For this natural laminar flow airfoil, we use two different flight conditions, varying both the Reynolds number and the angle of attack. For both conditions, the Mach number is 0.1. For condition 1, the angle of attack is zero and the Reynolds number is 4 million. In flight condition 2, the angle of attack is 4 degrees, with a 2 million Reynolds number. Numerical results for Xfoil and PSE (Halila *et al.*, 2019b) are shown in Table 1 along with wind tunnel data available in the literature (Somers, 1981).

Table 1. Transition locations computed with Xfoil, PSE, and from experimental data for the NLF(1)-0416 airfoil.

Condition, side	XFOIL (x_{tr}/c)	PSE (x_{tr}/c)	Experiment (x_{tr}/c)
1, upper	0.4223	0.375	0.385
1, lower	0.615	0.497	0.525
2, upper	0.371	0.291	0.310
2, lower	0.667	0.570	0.640

By inspecting the results shown in Table. 1, we point out that Xfoil has, for the analyzed conditions, some degree of inaccuracy when compared to the PSE and experimental results. We performed a mesh convergence study to guarantee mesh independence, and the seemingly inaccurate results correspond to a fully converged solution. Once again, we suspect that slight inaccuracies in the Xfoil H_k computations, as shown in Fig. 3, are leading to these discrepancies in transition front location.

When evaluating the transition front, Xfoil actually has a better agreement with experimental data than the PSE approach for the airfoil pressure side in flight condition 2. As pointed out in the literature (Halila *et al.*, 2019b), the PSE approach, being a parabolized method, is not able to directly account for transition triggered by laminar separation bubbles (LSB), which is the case for the airfoil pressure side in flight condition 2. Instead, the transition location is taken as the point in which the boundary layer solver, which is also parabolic in nature, diverges. This can be further improved through the use of empirical correlations that, given the bubble location and characteristics, indicate the transition front. In Xfoil, a similar approach based on empirical correlations is used, explaining its good agreement with wind tunnel data for the LSB-triggered transition we see in the pressure side for the NLF(1)-0416 airfoil.

For both flight conditions, the aerodynamic coefficients as predicted by Xfoil and CFD computations (Halila *et al.*, 2019b) can be seen to match well, which is a good indicative of the capabilities of Xfoil to predict relevant aerodynamic data. Results for lift and drag coefficients are summarized in Table 2. It is interesting to observe that the deviations in transition front location are not significantly compromising Xfoil's ability to predict the aerodynamic coefficients.

Table 2. Lift and drag coefficients computed with Xfoil, PSE, and from experimental data for the NLF(1)-0416 airfoil.

Condition	XFOIL(c_l)	CFD-PSE (c_l)	Experiment (c_l)	XFOIL (c_d)	CFD-PSE (c_d)	Experiment (c_d)
1	0.485	0.486	0.447	0.0052	0.0055	0.0059
2	0.941	0.937	0.880	0.0073	0.0077	0.0078

6. CONCLUDING REMARKS

The inclusion of transition to turbulence effects in fluid flows is relevant because laminar and turbulent states can coexist in many flight conditions. While high-fidelity transition prediction tools are able to correctly predict a number of relevant transition mechanisms, their computational cost may be incompatible with the fast turnaround times commonly observed in conceptual and preliminary design phases. Lower fidelity tools augmented with empirical transition prediction capabilities can be effectively used in the early design phases, while higher-fidelity methods can be saved for more detailed design phases or used to further investigate some phenomena not captured by the low-fidelity approaches.

In this paper, we assess the transition prediction capabilities in Xfoil, a panel method code that includes viscous effects through boundary layer estimations. In Xfoil, a two-field approach is used to combine inviscid and viscous flow regions. Xfoil uses a simplified e^N approach to detect the transition location. The user is able to input the critical N-factor, which encapsulates the freestream turbulence effects. Xfoil is tailored to investigate incompressible flows over single element airfoils.

We compare transitional flow results obtained by using Xfoil with those corresponding to a higher-fidelity approach based on the parabolized stability equations. We observe that Xfoil is able to correctly capture the upstream movement of the transition front caused by increasing freestream turbulence intensity. Additionally, Xfoil correctly captures the trend of transition front moving toward the leading edge as the chord-based Reynolds number is increased. We also report some mismatches between the transition onset locations computed by Xfoil when experimental and higher-fidelity numerical data are used. We believe that these numerical differences are caused by the local shape factor (H_k) estimates used by Xfoil. Despite these mismatches, Xfoil is able to accurately estimate lift and drag coefficients for the test cases investigated in this paper. Future investigations will include an investigation of Xfoil's ability to compute transition to turbulence caused by laminar separation bubbles. We will also address alternatives to the shape factor calculations in Xfoil with the goal of improving its transition prediction capabilities.

7. REFERENCES

- Bertolotti, F.P., Herbert, T. and Spalart, P.R., 1992. "Linear and nonlinear stability of the blasius boundary layer". *Journal of Fluid Mechanics*, , No. 242, pp. 441–474. doi:10.1017/S0022112092002453.
- Coder, J.G., 2019. "Further development of the amplification factor transport transition model for aerodynamic flows". In AIAA Paper No. 2019-0039, *Proceedings of the AIAA Scitech 2019 Forum*. San Diego, CA. doi:10.2514/6.2019-0039.
- Coder, J.G. and Maughmer, M.D., 2014. "Computational fluid dynamics compatible transition modeling using an amplification factor transport equation". *AIAA Journal*, Vol. 52, No. 11, pp. 2506–2512. doi:10.2514/1.J052905.
- Drela, M. and Giles, M.B., 1987a. "Ises - a two-dimensional viscous aerodynamic design and analysis code". *AIAA 25th Aerospace Sciences Meeting*. doi:10.2514/6.1987-424.
- Drela, M. and Giles, M.B., 1987b. "Viscous-inviscid analysis of transonic and low reynolds number airfoils". *AIAA Journal*, Vol. 25, pp. 1347–1355.
- Halila, G.L.O., Antunes, A.P., da Silva, R.G. and Azevedo, J.L.F., 2016a. "Effects of the boundary layer transition on the global aerodynamic coefficients". In *Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences*. Daejeon, South Korea.
- Halila, G.L.O., Antunes, A.P., Silva, R.G. and Azevedo, J.L.F., 2019a. "Effects of boundary layer transition on the aerodynamic analysis of high-lift systems". *Aerospace Science and Technology*, Vol. 90, pp. 233–245. doi:10.1016/j.ast.2019.04.051.
- Halila, G.L.O., Bigarella, E.D.V., Antunes, A.P. and Azevedo, J.L.F., 2018. "An efficient setup for freestream turbulence on transition prediction over aerospace configurations". *Aerospace Science and Technology*, Vol. 81, pp. 259–271. doi:10.1016/j.ast.2018.08.013.
- Halila, G.L.O., Bigarella, E.D.V. and Azevedo, J.L.F., 2016b. "A numerical study on transitional flows using a correlation-based transition model". *Journal of Aircraft*, Vol. 53, No. 4, pp. 922–941. doi:10.2514/1.C033311.
- Halila, G.L.O., Chen, G., Shi, Y., Fidkowski, K.J., Martins, J.R.R.A. and Mendonça, M., 2019b. "High-reynolds number transitional flow prediction using a coupled discontinuous-Galerkin rans pse framework". *Aerospace Science and Technology*, Vol. 91, pp. 321–336. doi:10.1016/j.ast.2019.05.018.
- Halila, G.L.O., Fidkowski, K.J. and Martins, J.R.R.A., 2021. "Toward automatic parabolized stability equation-based transition-to-turbulence prediction for aerodynamic flows". *AIAA Journal*, Vol. 59, No. 2, pp. 462–473. doi:10.2514/1.J059516.
- Halila, G.L.O., Martins, J.R.R.A. and Fidkowski, K.J., 2020. "Adjoint-based aerodynamic shape optimization including transition to turbulence effects". *Aerospace Science and Technology*, Vol. 107, p. 106243. doi:10.1016/j.ast.2020.106243.
- Hess, J. and Smith, A.M.O., 1964. "Calculation of nonlifting potential flow about arbitrary three dimensional bodies". *Journal of Ship Research*, Vol. 8, pp. 22–24.
- Juniper, M.P., Hanifi, A. and Theofilis, V., 2014. "Modal stability theory. lecture notes from the flow-nordita summer school on advanced instability methods for complex flows. stockholm, sweden, 2013". *Applied Mechanics Reviews*, Vol. 66, pp. 1–22. doi:10.1115/1.4026604.
- Langtry, R.B. and Menter, F.R., 2009. "Correlation-based transition modeling for unstructured parallelized computational fluid dynamics codes". *AIAA Journal*, Vol. 47, No. 12, pp. 2894–2906. doi:10.2514/1.42362.
- Langtry, R.B., Sengupta, K., Yeh, D.T. and Dorgan, A.J., 2015. "Extending the $\gamma - re_{\theta}$ local correlation based transition model for crossflow effects". In AIAA Paper No. 2015-2474, *22nd AIAA Computational Fluid Dynamics Conference*. Dallas, Tx.
- M. Drela, H.Y., 2001. *XFOIL 6.9 User Primer*. MIT Department of Aeronautics and Astronautics.
- Mack, L.M., 1977. "Transition prediction and linear stability theory". AGARD Report CP224.
- Shi, Y., Mader, C.A., He, S., Halila, G.L.O. and Martins, J.R.R.A., 2020. "Natural laminar flow airfoil design using a discrete adjoint approach with RANS- e^{ν} transition prediction". *AIAA Journal*, Vol. 58, No. 11. doi:10.2514/1.J058944.
- Somers, D.M., 1981. "Design and experimental results for a natural-laminar-flow airfoilfor general aviation applications". NASA TP-1981-1861, NASA.

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