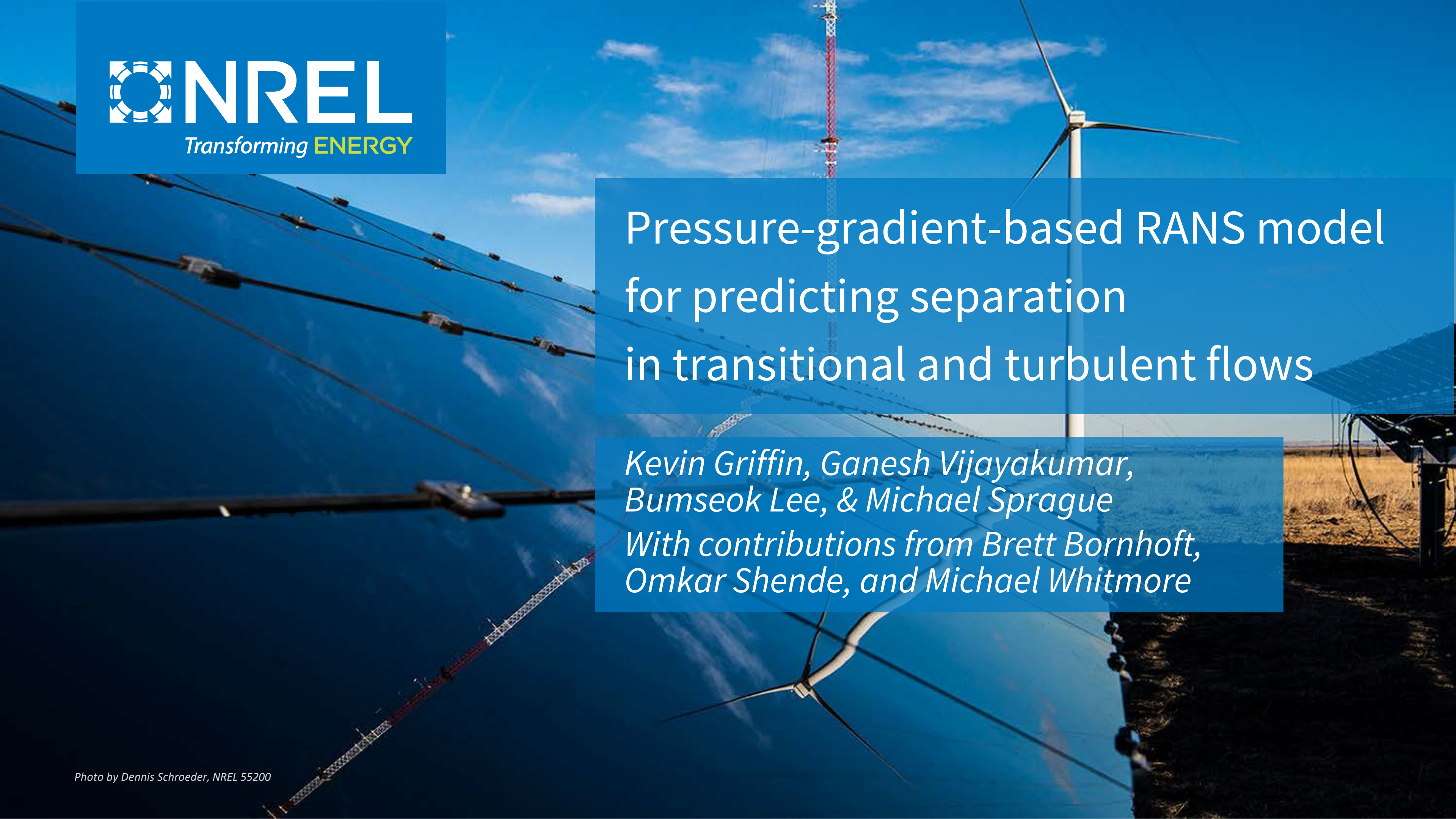


Photo by Dennis Schroeder, NREL 55200

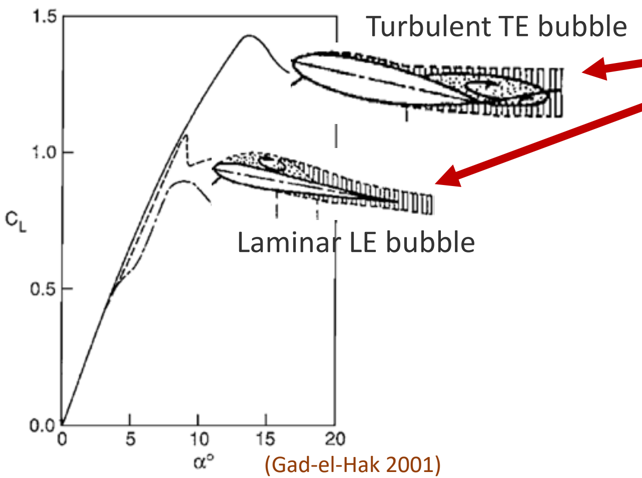
NREL
Transforming ENERGY

Pressure-gradient-based RANS model for predicting separation in transitional and turbulent flows

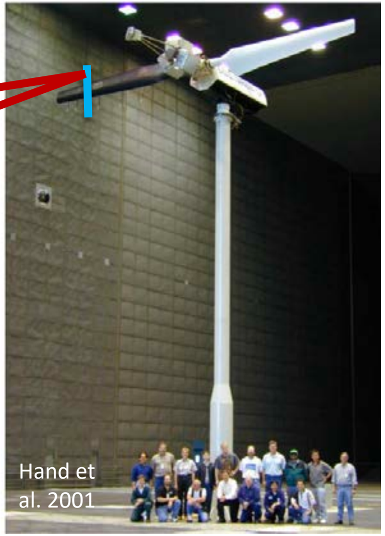
Kevin Griffin, Ganesh Vijayakumar, Bumseok Lee, & Michael Sprague

With contributions from Brett Bornhoft, Omkar Shende, and Michael Whitmore

Can we improve RANS predictions of separation in the context of transition?



(Gad-el-Hak 2001)



k-ω SST model

- Widely used for separation prediction
- Transport equations for k and ω
- SST equation for eddy viscosity [1]

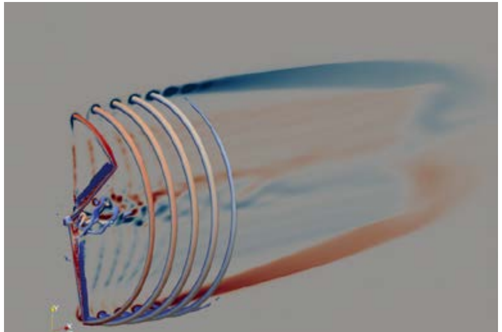
$$\mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, S F_2)}$$

- Transport equation for intermittency, which enters production and destruction terms for k [2]

[1] Menter et al. 2003
[2] Menter et al. 2015

Computational Setup

- Nalu-Wind
  - https://github.com/exawind/nalu-wind
  - Sharma et al. *Wind Energy* (2024)



Shreyas Ananthan, NREL

Separation model formulation

- Separation criterion

$$\lambda_\theta = -\frac{\theta^2}{\mu U}\frac{dP}{ds}$$

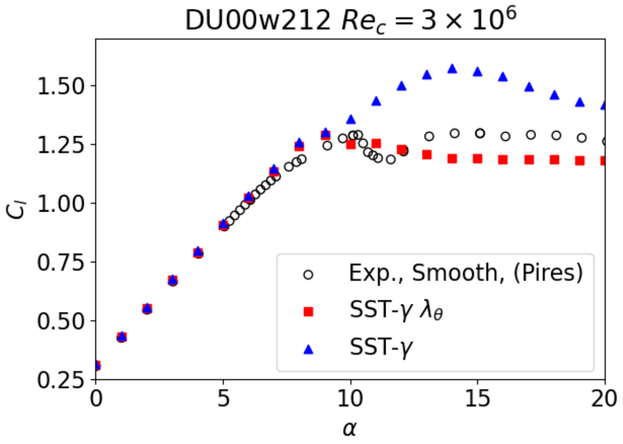
- Proposed composite critical value [1] uses intermittency γ

$$\lambda_{\theta,c} \equiv (1-\gamma)\underbrace{\lambda_{\theta,\mathrm{c,FS}}}_{\text{Laminar Falkner-Skan criterion}} + \gamma\,\underbrace{\Gamma(Re_\theta)^{3/4}}_{\text{Turbulent Buri criterion [2]}}$$

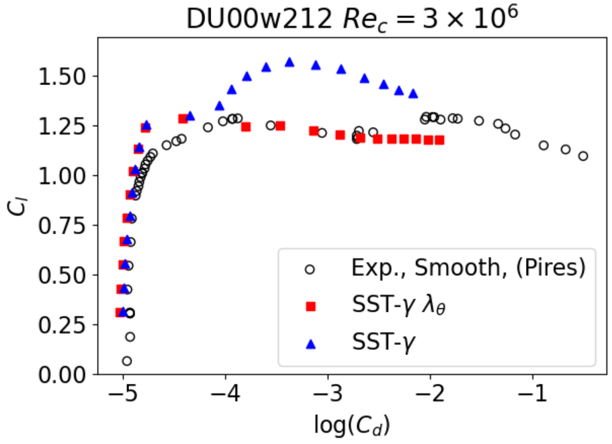
- Recalibrate eddy viscosity in separated regions
  - $\nu_t = \frac{a_1 k}{SF_2}$
  - If $\lambda_\theta < \lambda_{\theta,\mathrm{c}},\ a_1 = a_{1,\mathrm{sep}}$

[1] Griffin et al. *Proc. of the CTR Sum. Prog.* (2024)
[2] Buri *Min. Aircraft Prod.* (1931)

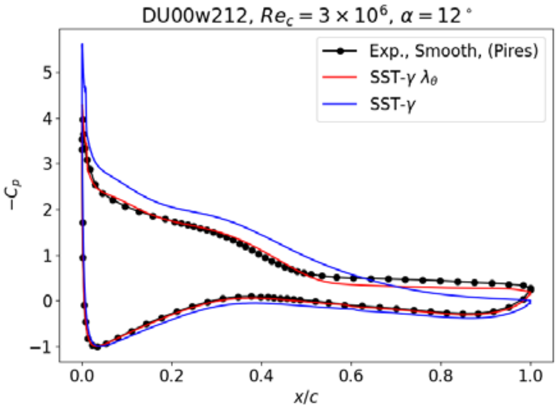
Results for a 20% thickness airfoil



Lift

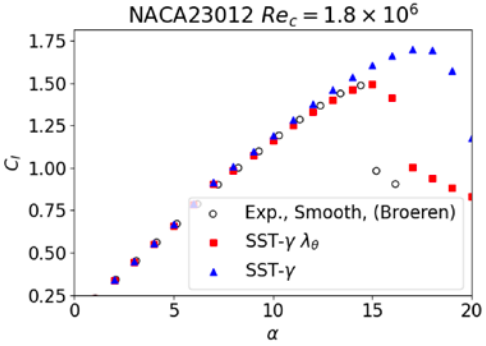


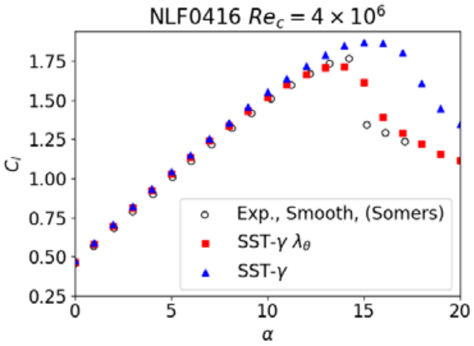
Drag

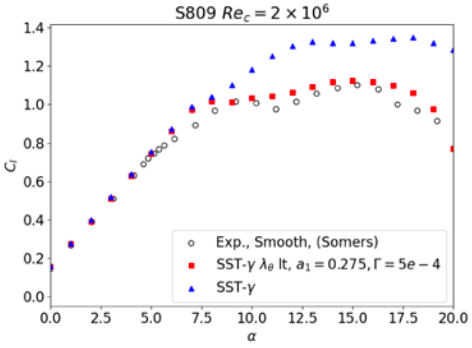


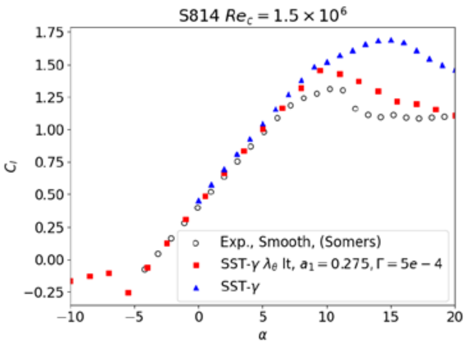
Pressure

Various smooth airfoils

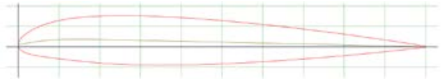




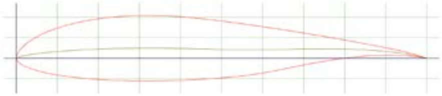




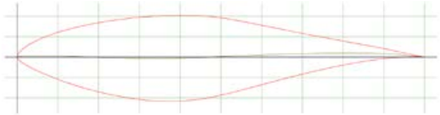
12% thickness



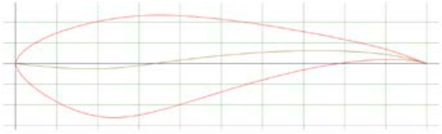
16% thickness



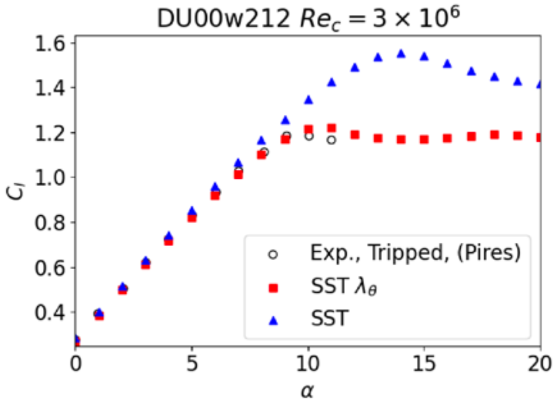
21% thickness



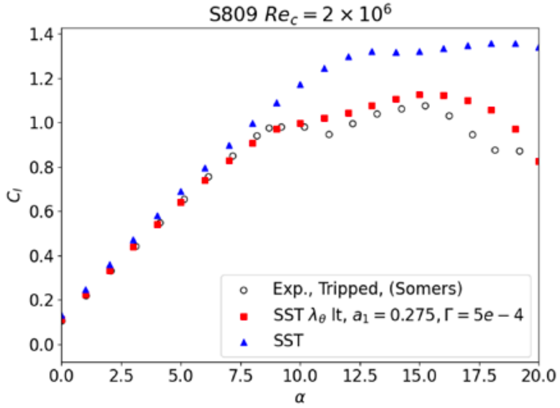
24% thickness



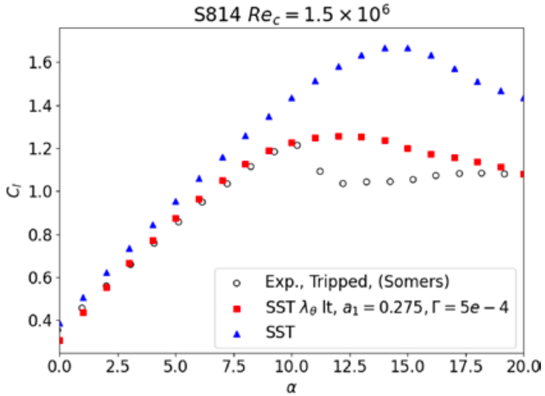
Various tripped airfoils



20% thickness



21% thickness

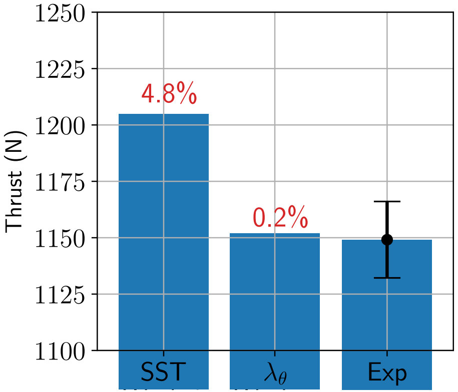


24% thickness

Application to a 3D case with rotation

NREL Phase VI Rotor

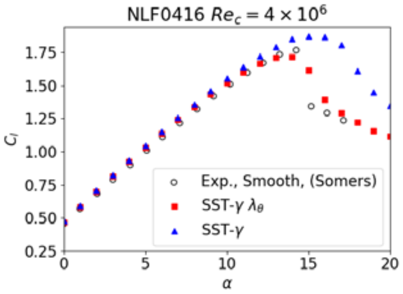
U_∞ = 7 m/s, D = 10.5 m, 72 RPM

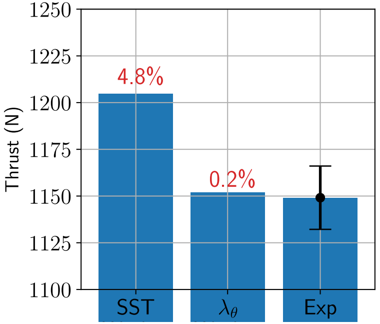


Proposed model improves the prediction of thrust

Conclusions

- Proposed a separation sensor for the SST RANS model which uses intermittency to switch between laminar and turbulent criteria
- Improves stall prediction for the flow over transitional and fully turbulent airfoils
- Improves thrust prediction for NREL Phase VI rotor





For more details: K.P. Griffin, B. Lee, G. Vijayakumar, B. Bornhoft, O.B. Shende, M.P. Whitmore. "Pressure-gradient-based RANS model for separation in transitional and turbulent flows ." *Proc. of the CTR Summer Program* (2024)

Acknowledgements:

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the Exascale Computing Project (Grant17-SC-20SC). Funding was also provided by the DOE Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The research was performed using computational resources sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and located at the National Renewable Energy Laboratory. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

k-omega SST model

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho u_j k}{\partial x_j} = P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}],$$

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial \rho u_j \omega}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j}[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}] + 2(1 - F_1)\frac{\rho \sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j},$$

$$\mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, S F_2)}$$

Menter et al. 2003

1-eqn transition model

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \tilde{P}_k + P_k^{\lim} - \tilde{D}_k + \frac{\partial}{\partial x_j}\left((\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right)$$

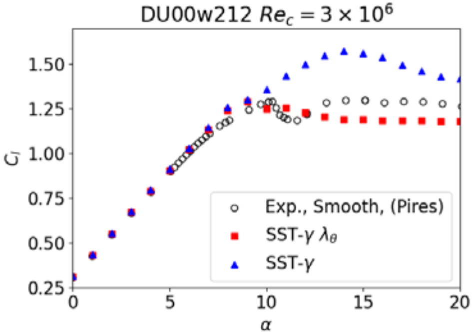
$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_j}(\rho u_j \omega) = \alpha \frac{P_k}{\nu_t} - D_\omega + Cd_\omega + \frac{\partial}{\partial x_j}\left((\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right)$$

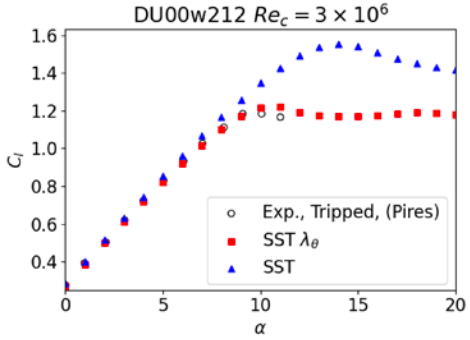
$$\tilde{P}_k = \gamma\, P_k$$

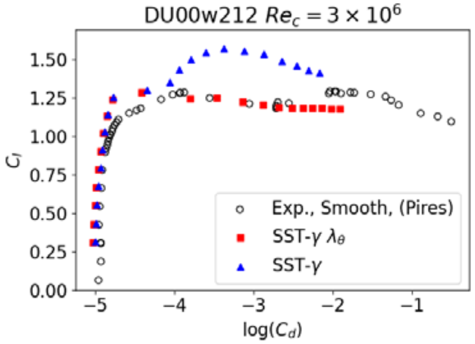
$$\tilde{D}_k = \max(\gamma, 0.1) \cdot D_k$$

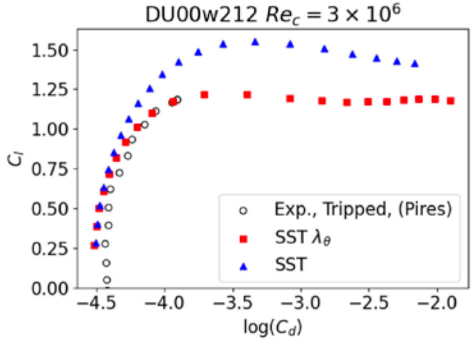
Menter et al. 2015

Smooth and tripped cases



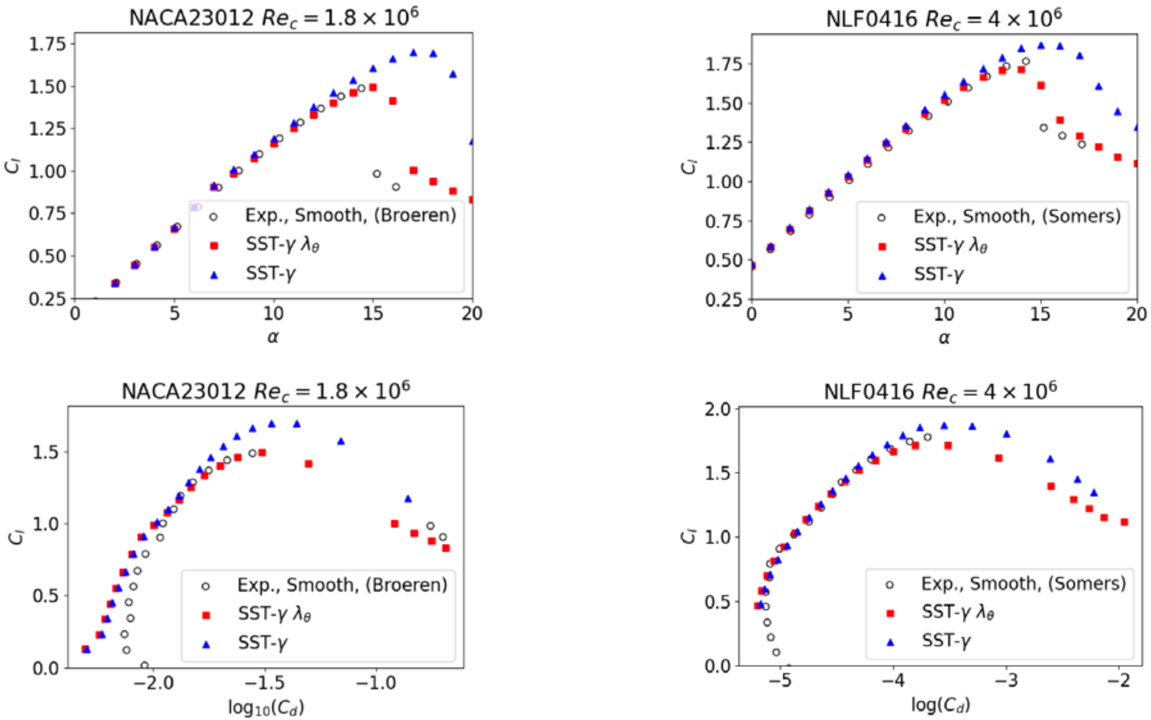






- Sensor works for smooth (transitional) and tripped cases

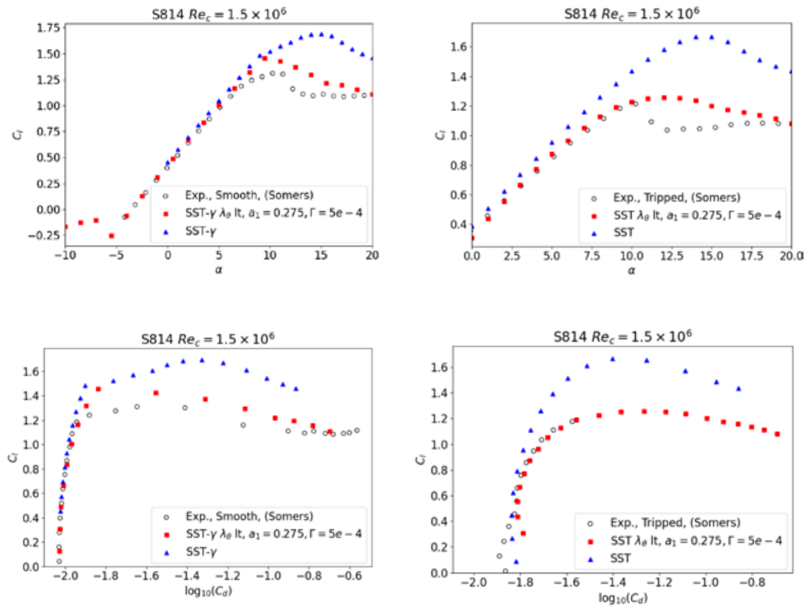
Thinner smooth airfoils



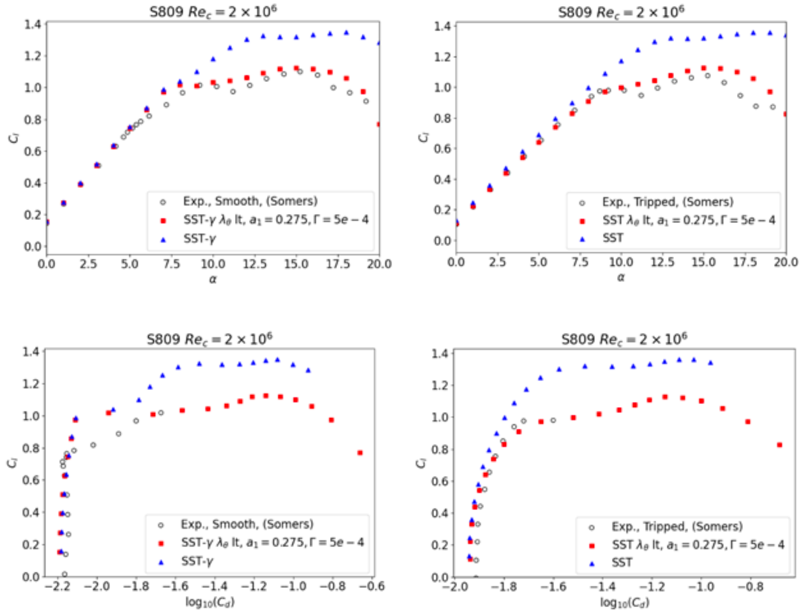
12% thickness

16% thickness

Thicker smooth/tripped airfoils



24% thickness



21% thickness