DGLR STAB-SYMPOSIUM 2024

Adjoint-Based Aerodynamic Shape Optimization with Free Laminar-Turbulent transition

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DLR Braunschweig and Göttingen

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Introduction

Goal:

Expending the DLR TAU code capabilities for gradient-based shape optimization with free laminar-turbulent transition.

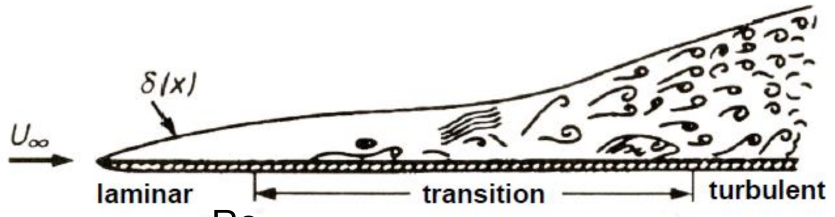
Motivation:

- Optimization processes based on fully turbulent solvers may lead to very inefficient NLF configurations. Transition location may play a role on the overall flow configuration, e.g. shock location and intensity, or flow separation.

Strategy:

- Integration of the DLR γ model coupled to the negative Spalart-Allmaras turbulence model into the adjoint solver of the DLR TAU code.

The DLR γ-SA-neg model



$Re_{\theta t}$

γ≈0 γ≈1

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

$$\frac{\partial \tilde{\nu}}{\partial t} + U_j \frac{\partial \tilde{\nu}}{\partial x_j} = P_{\tilde{\nu},\gamma} - D_{\tilde{\nu},\gamma} + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\nu + \tilde{\nu})\frac{\partial \tilde{\nu}}{\partial x_j}\right) + c_{b2}\frac{\partial \tilde{\nu}}{\partial x_j}\frac{\partial \tilde{\nu}}{\partial x_j}\right]$$

$$P_{\tilde{\nu},\gamma} = c_{b1}\left(1 - \boldsymbol{f_{t2,\gamma}}\right)\tilde{S}\tilde{\nu} \qquad D_{\tilde{\nu},\gamma} = \left(c_{w1} f_w - \frac{c_{b1}}{\kappa}\boldsymbol{f_{t2,\gamma}}\right)\left[\frac{\tilde{\nu}}{d}\right]^2$$

$$f_{t2,\gamma} = c_{t3}(1-\gamma) + c_{t3}\gamma\exp(-0.5\,\chi^2) \rightarrow f_{t2,\gamma} = \begin{cases} 1.2 & \text{if } \gamma = 0 \\ f_{t2} & \text{if } \gamma = 1 \end{cases}$$

- To keep $\chi = \tilde{\nu}/\nu \approx 0.6$ in the laminar region:

$$P_{\tilde{\nu},lam} = b_\chi c_{b1}\tilde{S}\tilde{\nu}; \qquad b_\chi = c_1\chi^4\exp(-c_2\chi^4)$$

The DLR γ-SA-neg model Overview[1]

[1] François D. G., Krumbein A. :"On the Coupling of a γ – based Transition Transport model to the Negative Spalart-Allmaras Turbulence Model", 3AF Conference, Toulouse, 2022

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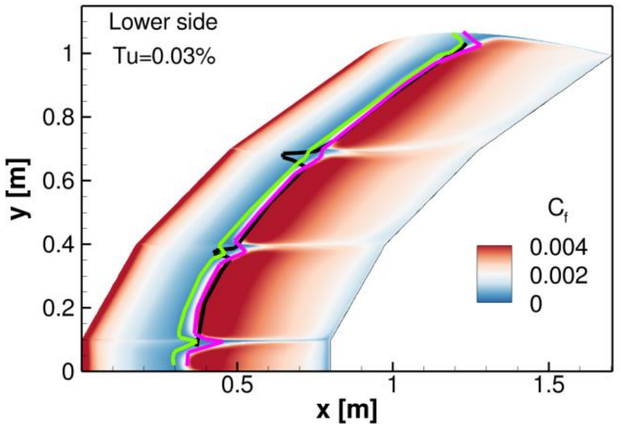
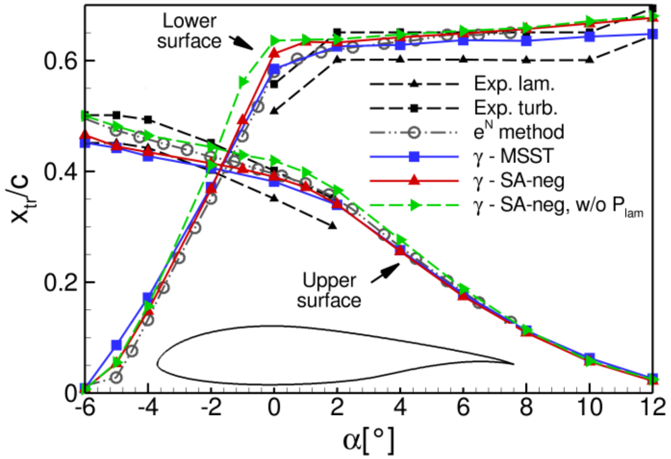
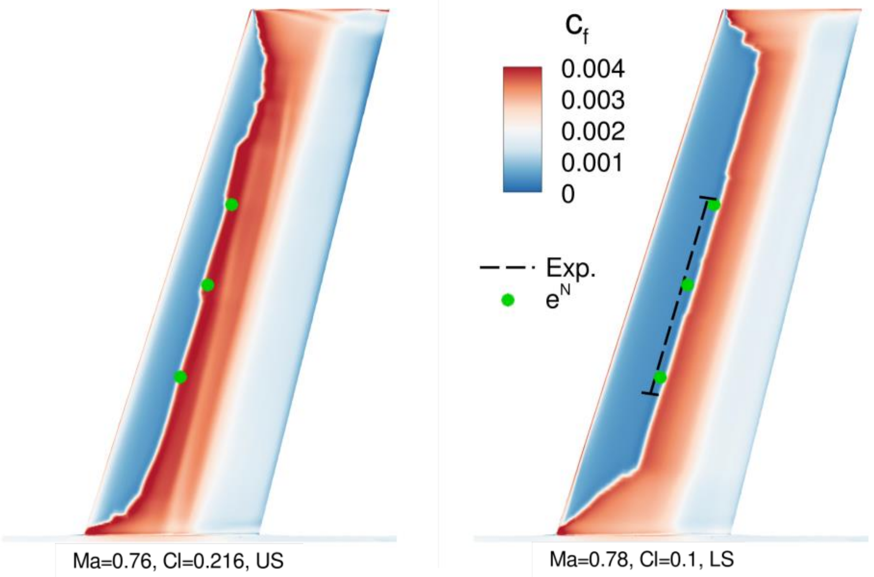
TU Braunschweig Sickle Wing:



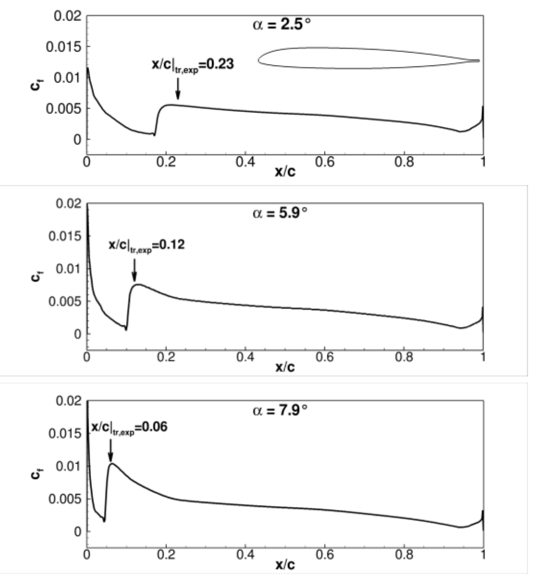
NLF(1)-0416 airfoil:



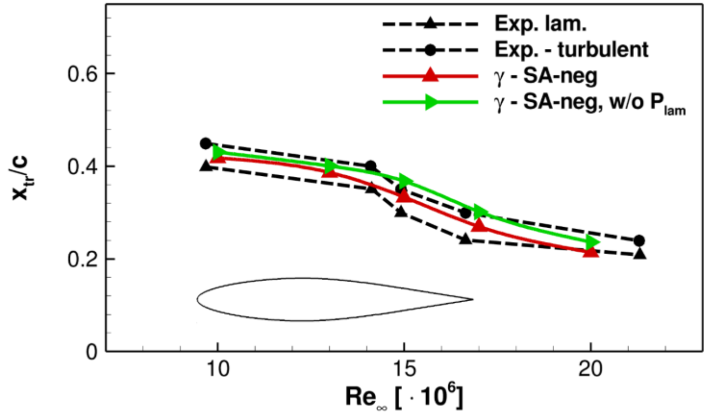
TELFONA Pathfinder Wing:



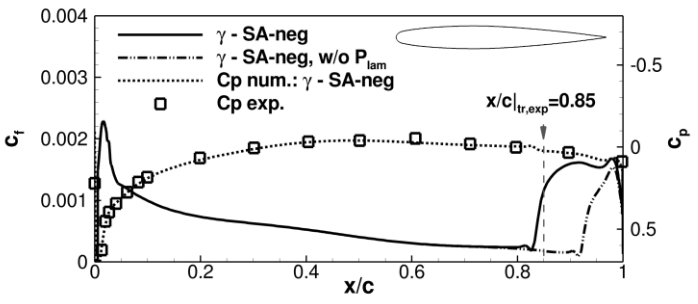
DSA-9A airfoil:



NACA64$_2$A015 airfoil:

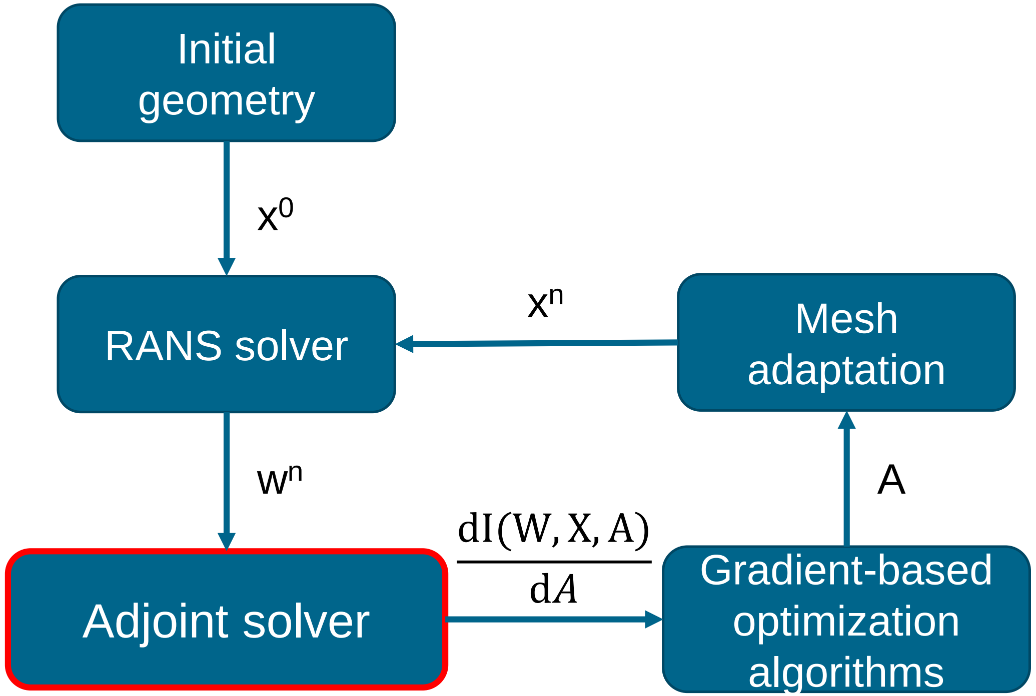


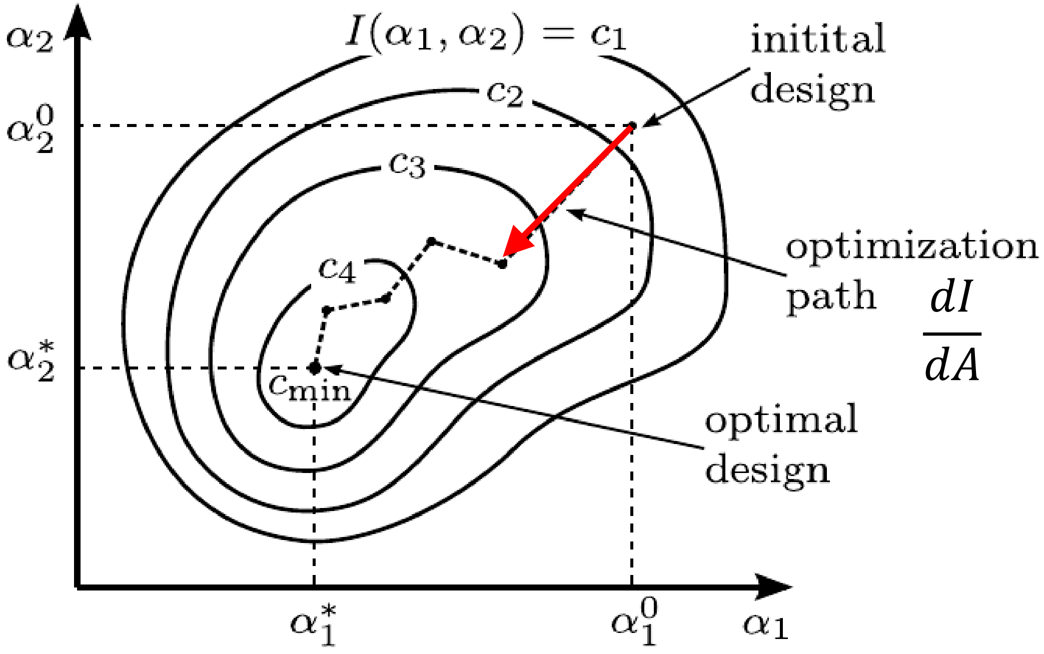
ONERA D ISW:



Optimization framework

$$I(W,X,A) = \varphi^{\text{current}}(W,X,A) - \varphi^{\text{target}}$$





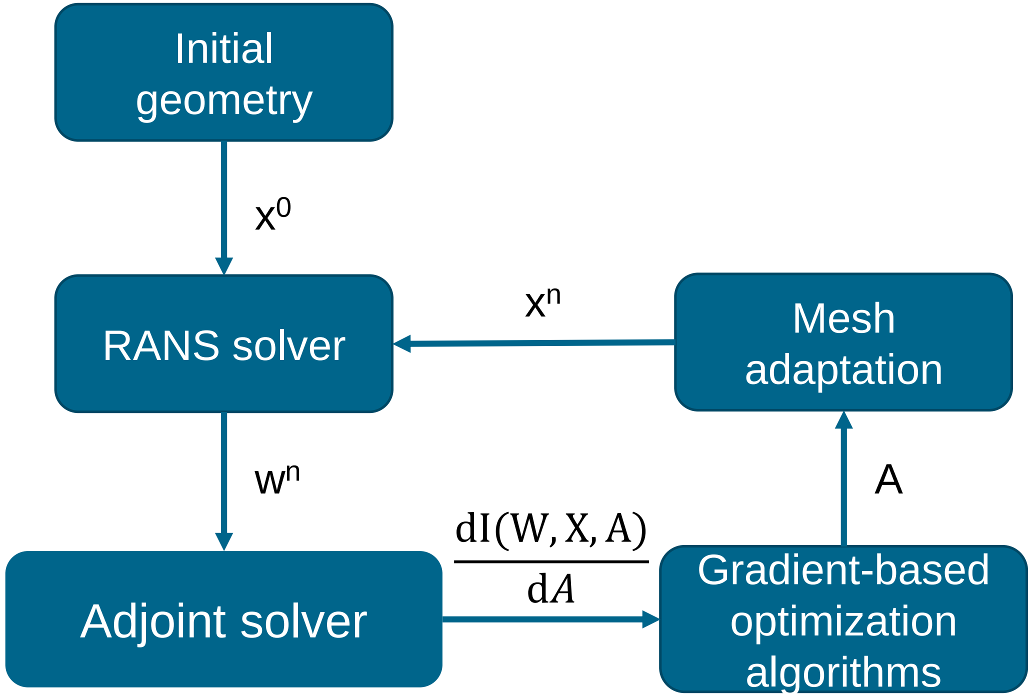
Source: TAU user guide

Optimization strategy

Python-based optimization framework

- Aerodynamic state: DLR TAU code with the DLR γ-SA-negative turbulence model.

- Cost function sensitivity: Gradients computed by the discrete adjoint solver of the DLR TAU code, whereas the design variables are define by the airfoil parametrization.
- Optimization: SNOPT (Sparse nonlinear optimizer).
- Mesh adaptation: TAU volume deformation module.



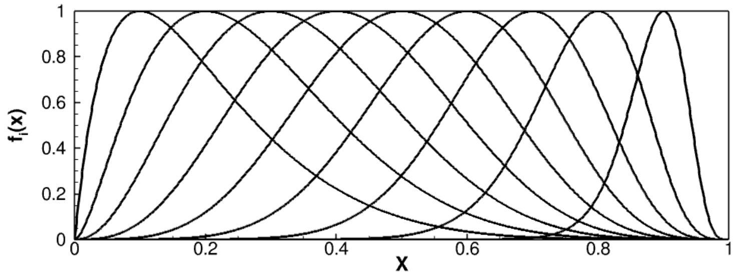
Optimization framework

Aerodynamic shape parametrization

- Shape parametrization technique: weighted sum of Hicks-Henne “Bump” functions.

$$y = y_0 + \sum_{j=1}^{N} w_i f_i(x)$$

$$f_i(x) = \left[\sin\left(\pi x^{\frac{\log 0.5}{\log x_{max,i}}}\right)\right]^4$$



with 9 x_{max}-locations on the upper surface and 9 x_{max}-locations on the lower surface. → The weights w_i are the design variables of the optimization process.

Optimization framework

$$\text{Minimize } I = -\frac{L}{D}$$

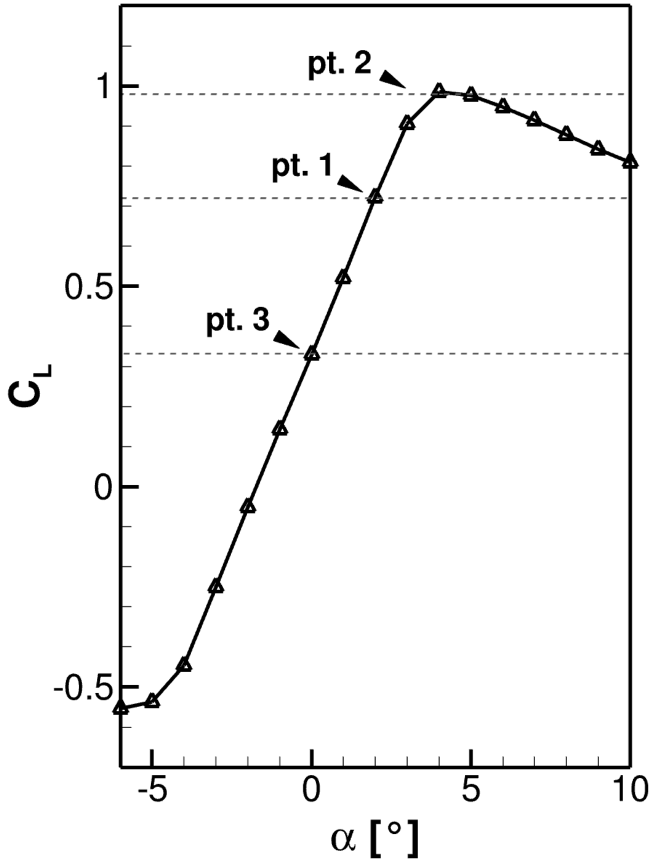
$$\text{while} \begin{cases} C_L = C_L^{\text{Target}} \\ C_{My} \geq C_{My,0} \\ Vol_{\text{airfoil}} \geq Vol_{\text{airfoil},0} - \Delta Vol_{\text{airfoil,max}} \end{cases}$$

- C_L^{Target} is obtained by adjusting α (target-lift mode) → Any change of the design variables, A, will result in a change of α to keep C_L^{Target}.

$$\alpha = \alpha(A)$$

Results

- Baseline airfoil: RAE2822.
- M=0.73, $Re_\infty = 23 \cdot 10^6$, $Tu_\infty = 0.1\%$.



Single points:

- Pt. 1: $C_L^{\text{Target}} = 0.72$
- Pt. 2: $C_L^{\text{Target}} = 0.98$
- Pt. 3: $C_L^{\text{Target}} = 0.331$

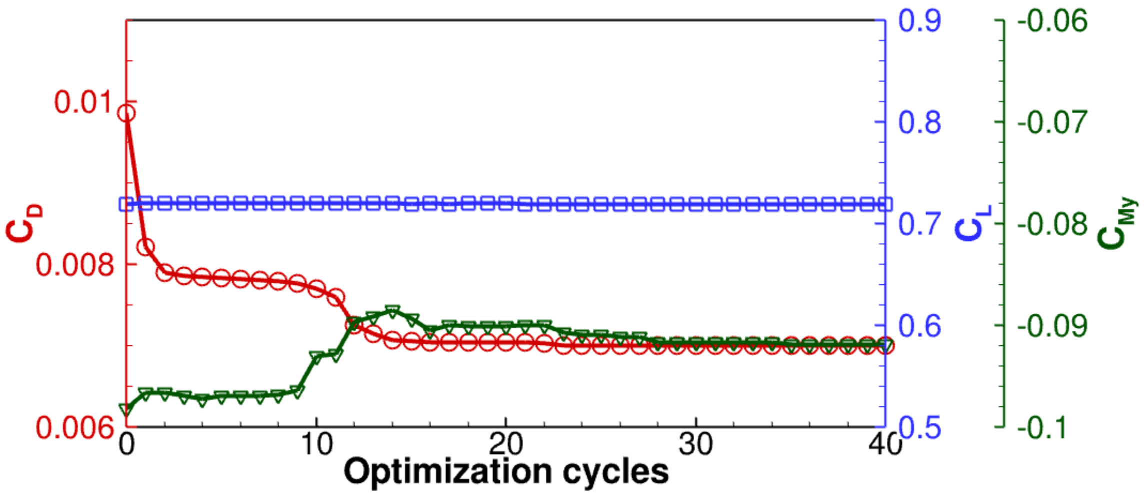
Multi-points:

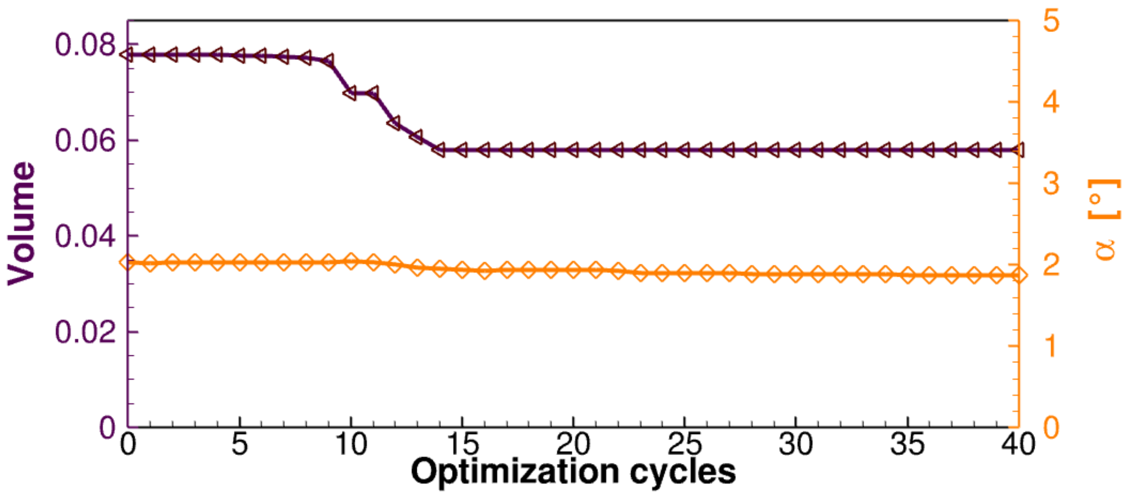
$$I = \sum_{i=1}^{3} w_i I_i$$

with $w_1 = 0.6$, $w_2 = 0.3$, and $w_3 = 0.1$.

Results

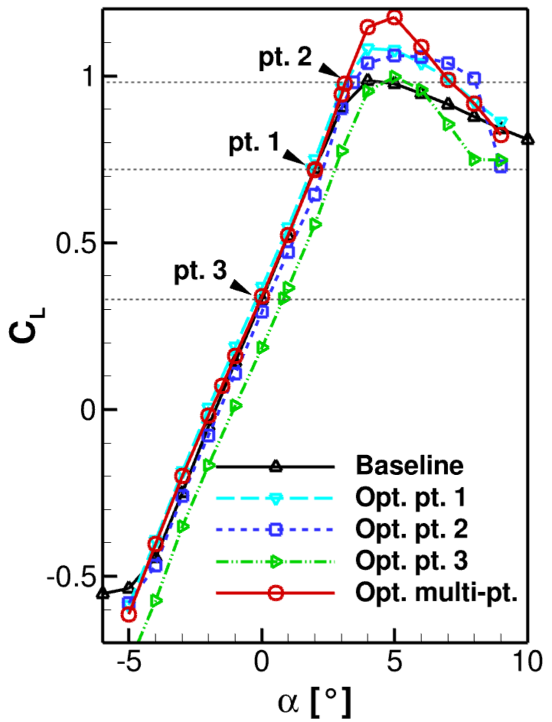
- Single point optimization for the design point 1 ($C_{L,target}$ = 0.72)

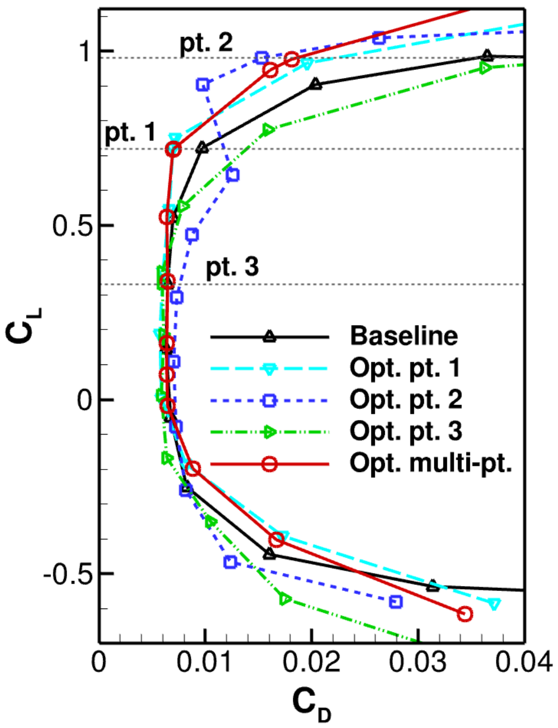


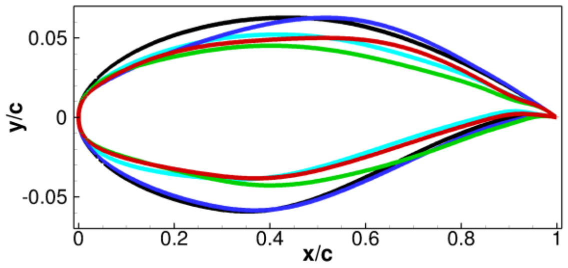


Results

- Comparison between single-point and multi-point optimization.



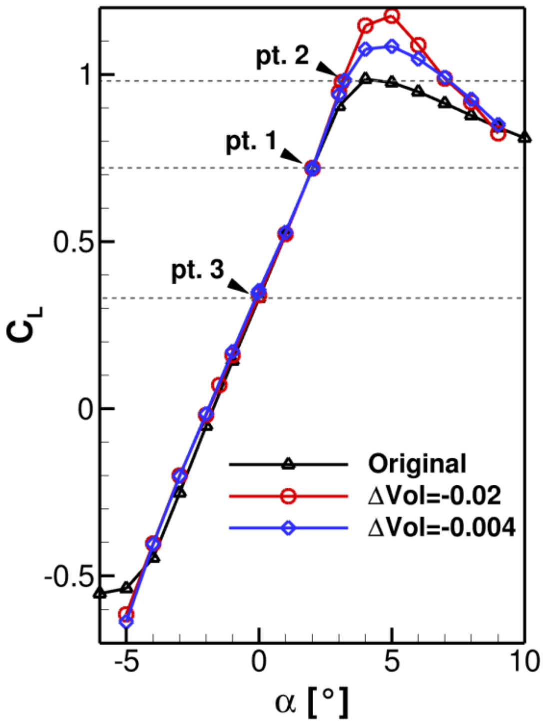


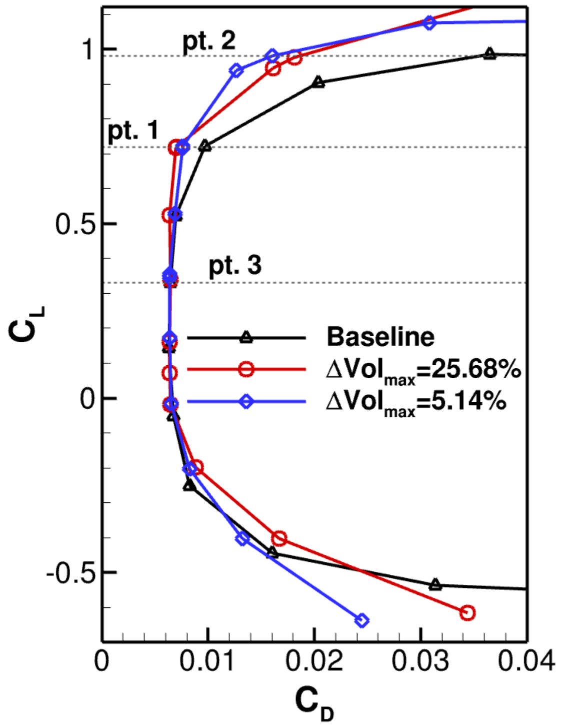


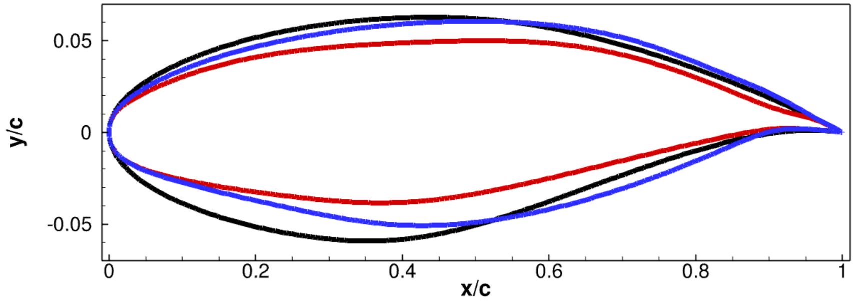
	Single-point		Multi-point	
	$\Delta C_D[\%]$	$\Delta Vol[\%]$	$\Delta C_D[\%]$	$\Delta Vol[\%]$
Pt. 1	-28.26	-25.68	-27.34	-25.68
Pt. 2	-54.07	-2.02	-44.72	-25.68
Pt. 3	-7.55	-25.68	0.1	-25.68

Results

- Comparison of volume reduction constraints.



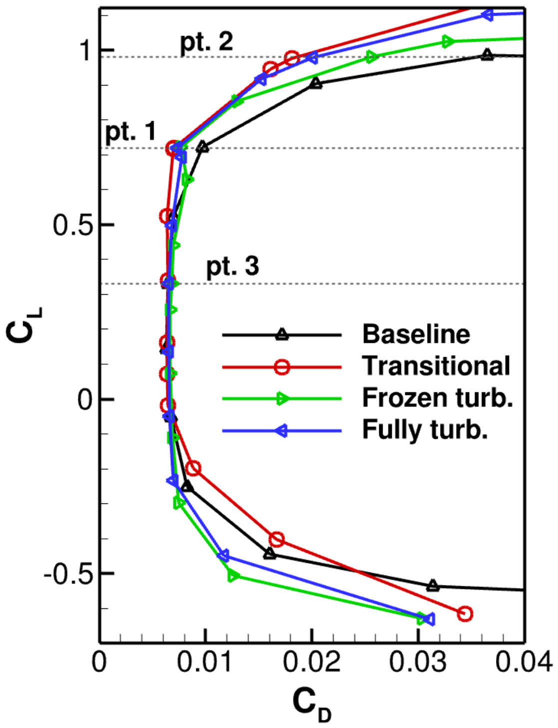


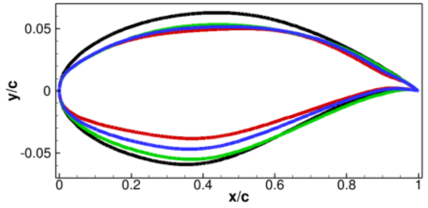


	$\Delta Vol_{\max}$ = 25.68		$\Delta Vol_{\max}$ = 5.14	
	$\Delta C_D[\%]$	$\Delta Vol[\%]$	$\Delta C_D[\%]$	$\Delta Vol[\%]$
Pt. 1	-27.34	-25.68	-21.42	-5.14
Pt. 2	-44.72	-25.68	-51.85	-5.14
Pt. 3	0.1	-25.68	-1.42	-5.14

Results

- Comparison of different optimization approach:





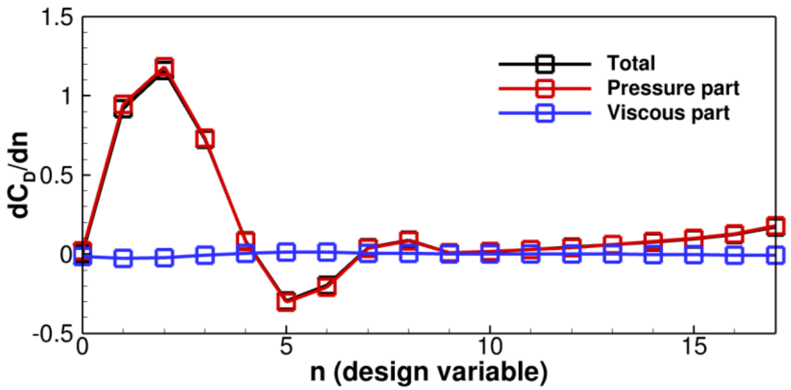
	Transitional		Frozen turbulence		Fully turbulent	
	$\Delta C_D[\%]$	$\Delta Vol[\%]$	$\Delta C_D[\%]$	$\Delta Vol[\%]$	$\Delta C_D[\%]$	$\Delta Vol[\%]$
Pt. 1	-27.34	-25.68	-20.10	-9.65	-24.30	-17.85
Pt. 2	-44.72	-25.68	-23.12	-9.65	-38.49	-17.85
Pt. 3	0.1	-25.68	5.04	-9.65	1.54	-17.85

Results

- Effect contributions to the drag reduction:

	Transitional		Frozen turbulence		Fully turbulent	
	ΔC_D^P [%]	ΔC_D^v [%]	ΔC_D^P [%]	ΔC_D^v [%]	ΔC_D^P [%]	ΔC_D^v [%]
Pt. 1	-51.12	-2.07	-42.07	3.23	-50.48	3.53
Pt. 2	-51.69	5.33	-27.25	6.52	-45.19	9.6
Pt. 3	-23.46	9.66	-5.16	9.18	-15.52	8.47

- At the design pt. 1 of the baseline airfoil, the viscous drag is 48% of the total drag. But, the viscous drag it is not minimize during the optimization
- Low sensitivity of the drag to viscous effects for shape design variables.



Conclusions

- Extension of the DLR TAU capabilities for gradient-based shape optimization with free laminar-turbulent transition.
- Verification through aerodynamic shape optimizations on the transonic RAE2822 airfoil, considering single-point and multi-point design conditions.
- Impact assessment of shape constraints and simplified optimization approaches.
- Low sensitivity of the viscous drag to shape design variables. → need for a stronger representation of the laminar extent in the optimized figure of merit to obtain the benefits of laminarization.

Q&A

Bildquelle hier angeben