STAB WORKSHOP 2023

Expeditious Evaluation of the Dynamic Response of Natural Laminar Flow Configurations to Small Pitching Oscillations

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DLR

Outline

- Motivation
- The DLR γ – SA-neg. model
- TAU Linear Frequency Domain (LFD) solver
- Verification
- Conclusions

Motivation

Modern aircraft design

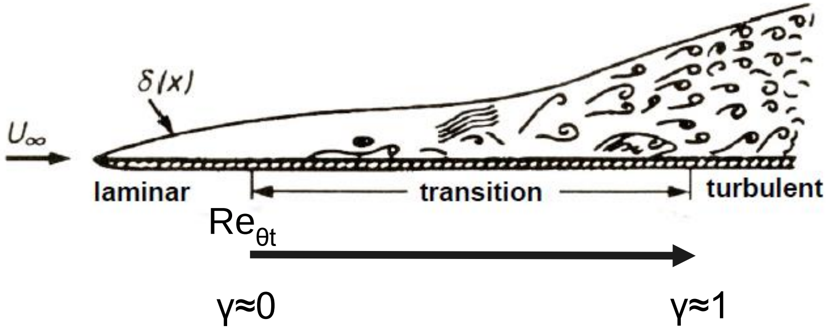
Higher cruise velocities + Lighter/more flexible structures = Risk of flutter

- Determining the aeroelastic stability boundary (flutter onset) at an early stage of the design process is crucial.
- Time-accurately solving the dynamic response to structural perturbations is prohibited in terms of computational cost . Wide rage of conditions need to be considered e.g. Mach, amplitude, altitude, loading, deformation mode shape and frequency).
- Assuming small harmonic perturbations, the Linear Frequency Domain (LFD) method can be use to linearly evaluate the dynamic response of the flow.

Higher cost-efficiency + Lower global warming effects ➡ Natural laminar aircraft designs

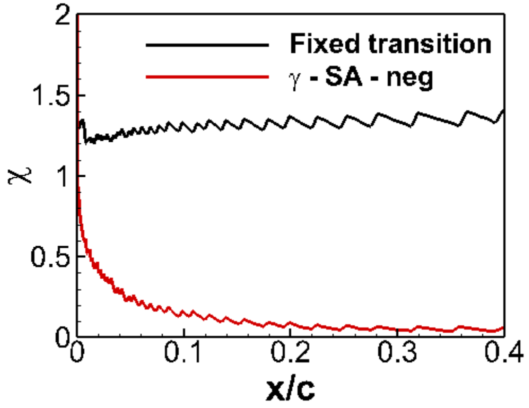
- The LFD solver of the DLR TAU code was extended to account for free transition effects.

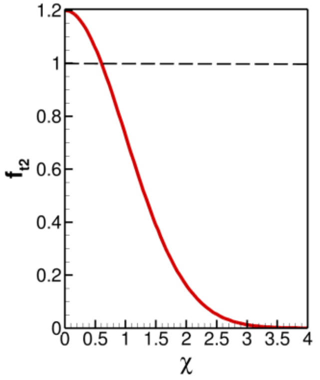
The DLR γ - SA-neg. model



$\chi_\infty = 3.79$

$f_{t2} = c_{t3}\exp(-c_{t4}\chi^2)$





$$\nu_t = \tilde{\nu}\cdot f_{v1} \qquad f_{v1} = \frac{\chi^3}{\chi^3 + 7.1^3} \qquad \chi = \frac{\tilde{\nu}}{\nu}$$

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

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

$$f_{t2,\gamma} = c_{t3}(1-\gamma) + c_{t3}\gamma\exp(c_{t4}\chi^2)$$

$$b_\chi = c_1\chi^4\exp(-c_2\chi^4)$$

- Negative formulation is unaffected

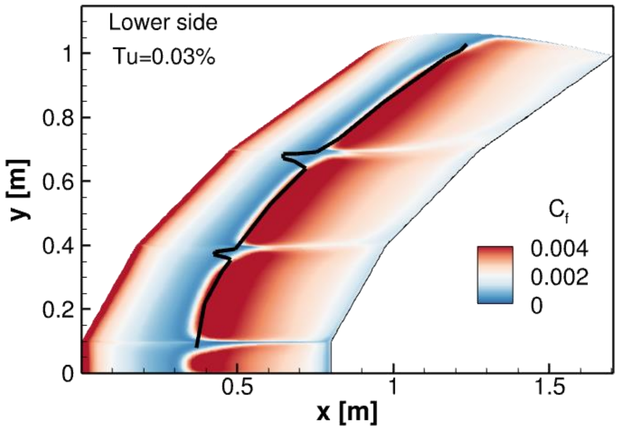
$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_j\gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

The DLR γ - SA-neg. model

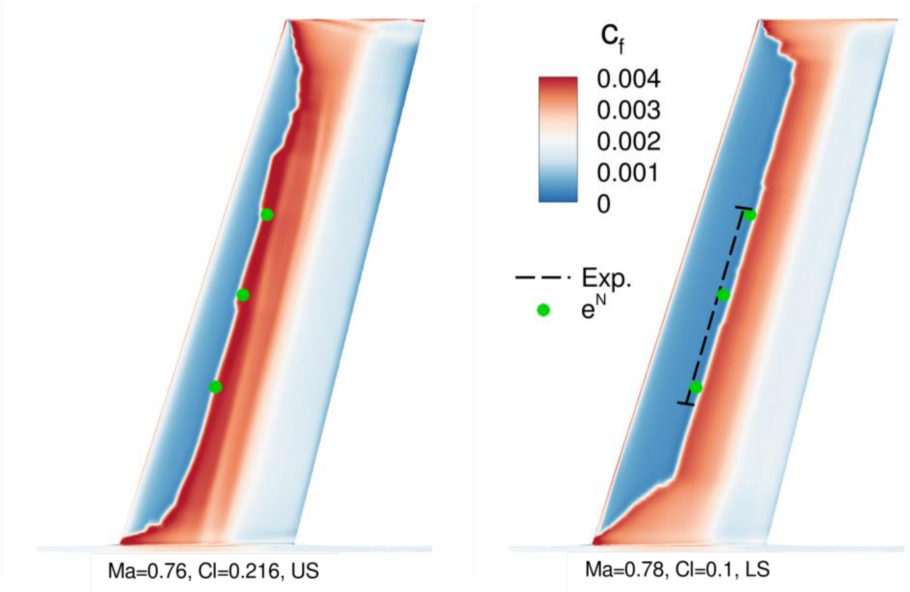
Overview[1]

[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

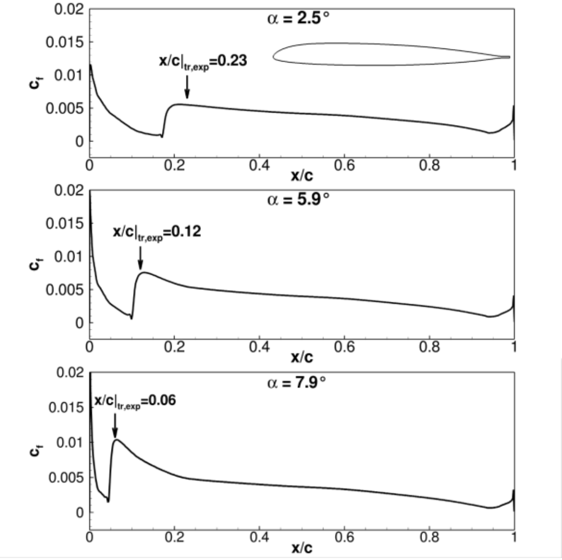
TU Braunschweig Sickle Wing:



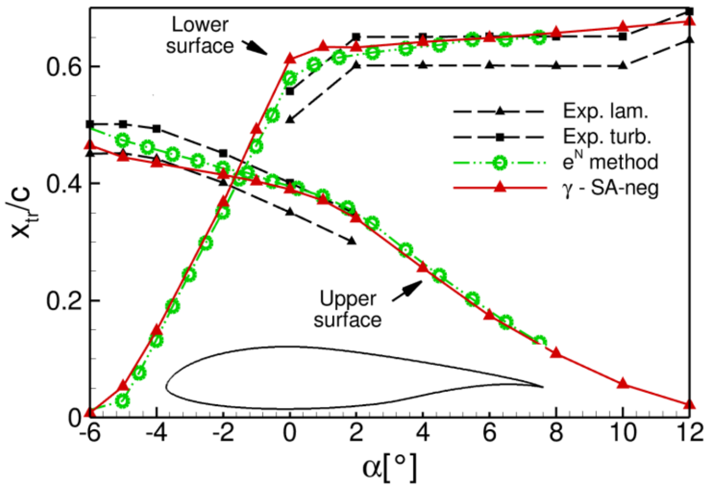
TELFONA Pathfinder Wing:



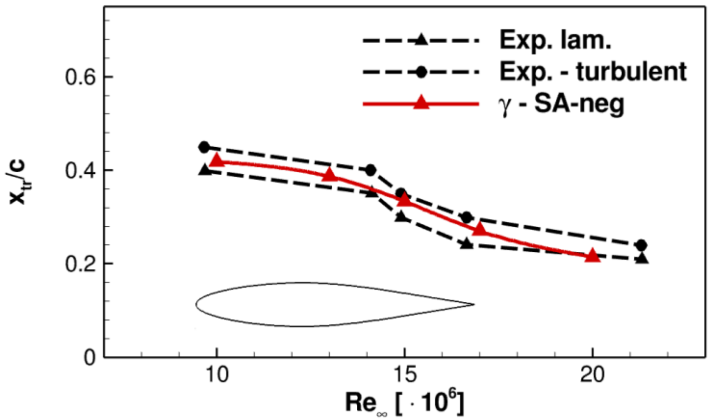
DSA-9A airfoil:



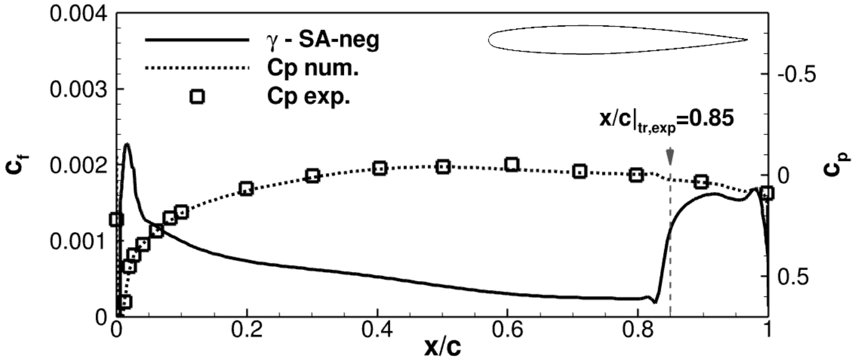
NLF(1)-0416 airfoil:



NACA64$_2$A015:



ONERA D ISW:



TAU Linear Frequency Domain (LFD) solver

- Linearization + conversion to frequency domain (first-harmonic of Fourier series)

$$R(W,x,\dot{x}) \approx R(\bar{W},\bar{x},\dot{\bar{x}}) + \left.\frac{\partial R}{\partial W}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \tilde{W} + \left.\frac{\partial R}{\partial x}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \tilde{x} + \left.\frac{\partial R}{\partial \dot{x}}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \dot{\tilde{x}} \qquad w/ \qquad \tilde{\varphi} = \hat{\varphi} e^{i\omega t}$$

- Conversion of RANS into a complex linear system

$$\left[i\omega + \frac{\partial R}{\partial W}\right]\hat{W} = -\left[\frac{\partial R}{\partial x} + i\omega\frac{\partial R}{\partial \dot{x}}\right]\hat{x}$$

- Splitting into two coupled real system, $\hat{W} = \mathrm{Re}\hat{W} + i\mathrm{Im}\hat{W}$ and $\hat{x} = \mathrm{Re}\hat{x} + i\mathrm{Im}\hat{x}$

$$\begin{bmatrix} \frac{\partial R}{\partial W} & -\omega \\ \omega & \frac{\partial R}{\partial W} \end{bmatrix} \begin{bmatrix} Re\hat{W} \\ Im\hat{W} \end{bmatrix} = \begin{bmatrix} \frac{\partial R}{\partial x} & -\omega\frac{\partial R}{\partial \dot{x}} \\ \omega\frac{\partial R}{\partial \dot{x}} & \frac{\partial R}{\partial x} \end{bmatrix} \begin{bmatrix} Re\hat{x} \\ Im\hat{x} \end{bmatrix}$$

→ Only valid for small perturbations, non-linear effects such as shifts in frequency or harmonic modes are neglected.

TAU Linear Frequency Domain (LFD) solver

- Vector of primitive variable: $W = [\overbrace{\rho\, u_1\, u_2\, u_3\, p}^{\widehat{W}}\, \tilde{\nu}\, \gamma]^T$
- Flux Jacobian ${}^{\partial R}/_{\partial W}$:

$$\begin{aligned} R^{\rho}(W,X,D) &= 0 \\ R^{u_i}(W,X,D) &= 0 \\ R^{p}(W,X,D) &= 0 \\ R^{\tilde{\nu}}(W,X,D) &= 0 \\ R^{\gamma}(W,X,D) &= 0 \end{aligned}$$

$$\frac{\partial R}{\partial W} = \begin{bmatrix} \frac{\partial R^{\widehat{W}}}{\partial \widehat{W}} & \frac{\partial R^{\widehat{W}}}{\partial \gamma} \\ \frac{\partial R^{\tilde{\nu}}}{\partial \widehat{W}} & \frac{\partial R^{\tilde{\nu}}}{\partial \gamma} \\ \frac{\partial R^{\gamma}}{\partial \widehat{W}} & \frac{\partial R^{\gamma}}{\partial \gamma} \end{bmatrix}$$

=0

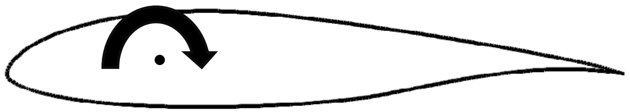
- Grid-node Jacobian ${}^{\partial R}/_{\partial x}$:

$$\frac{\partial R}{\partial W} = \left[\frac{\partial R^{\widehat{W}}}{\partial x} \quad \frac{\partial R^{\gamma}}{\partial x}\right]^T$$

- Analytical
- Finite difference (RHS FD)

Verification
NLF(1)-0416

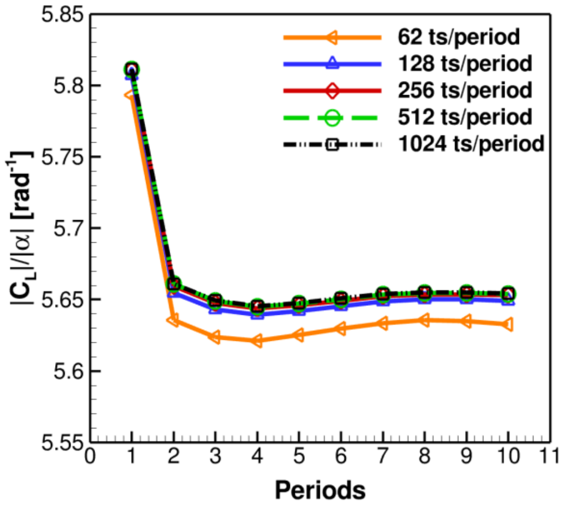
- Pitching motion about y at x/c = 0.25.
- Re = 4×10^6, Ma = 0.1, Tu_∞ = 0.03%.
- $\varepsilon = 10^{-5}$ for RHS FD approach.
- URANS: 5 periods with 256 time steps/period.

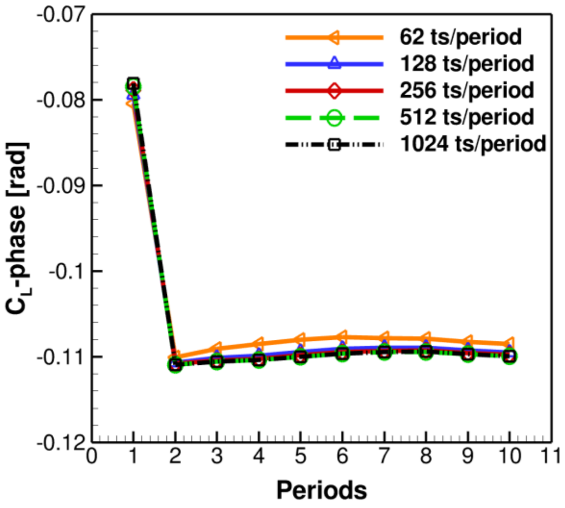


$$\alpha(\tau) = -4^\circ + 0.1^\circ \sin(k \cdot \tau)$$

$$k = \frac{2\pi f l_{\text{ref}}}{U_\infty} \qquad \tau = \frac{U_\infty t}{l_{\text{ref}}}$$

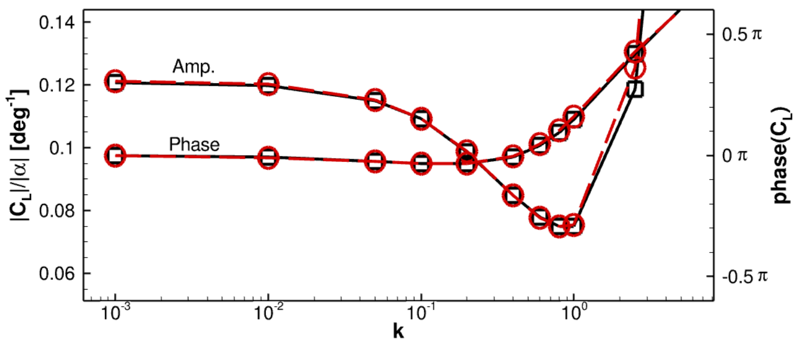
- Time convergence study of the first harmonic of the lift coefficient for a pitching motion of amplitude $\hat{\alpha} = 0.1^\circ$ and a reduced frequency of k=0.2.

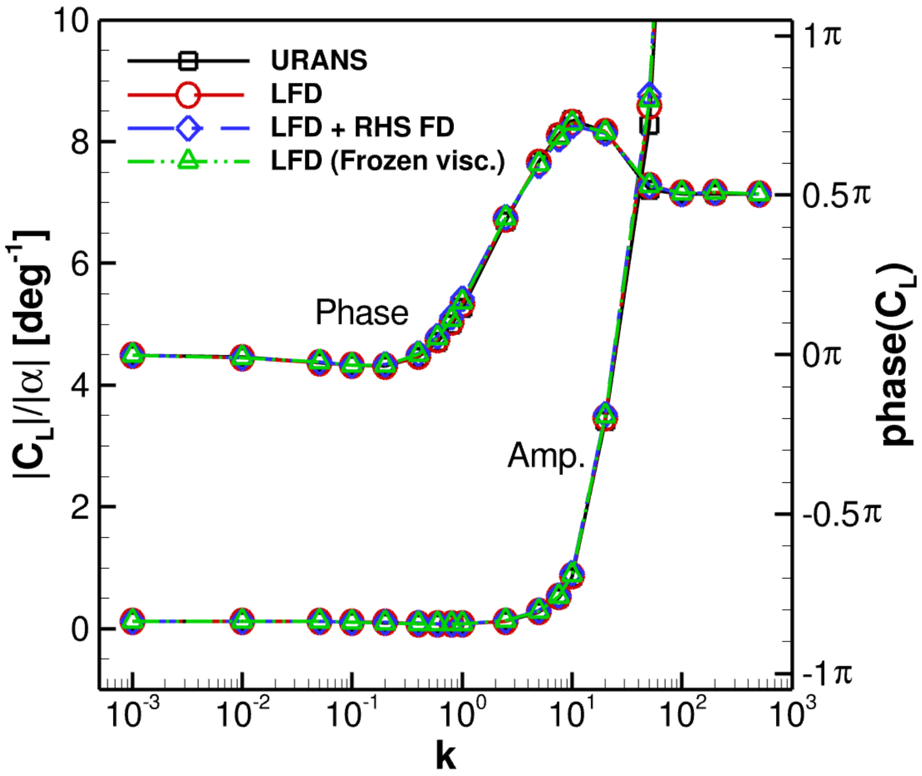


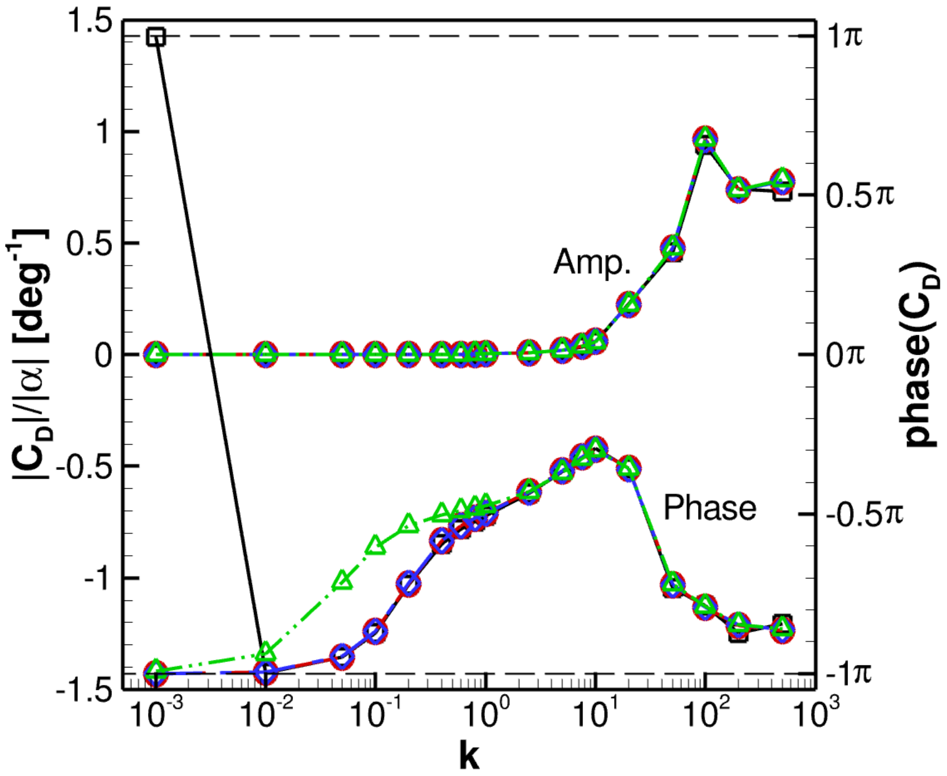


Verification
NLF(1)-0416

- First harmonic of the lift and drag coefficients for a pitching motion of amplitude $\hat{\alpha} = 0.1°$ as a function of the reduced frequency k:

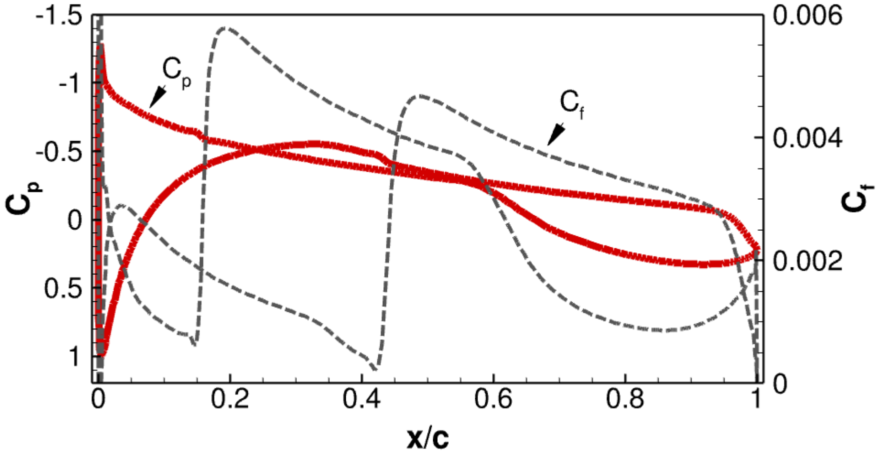


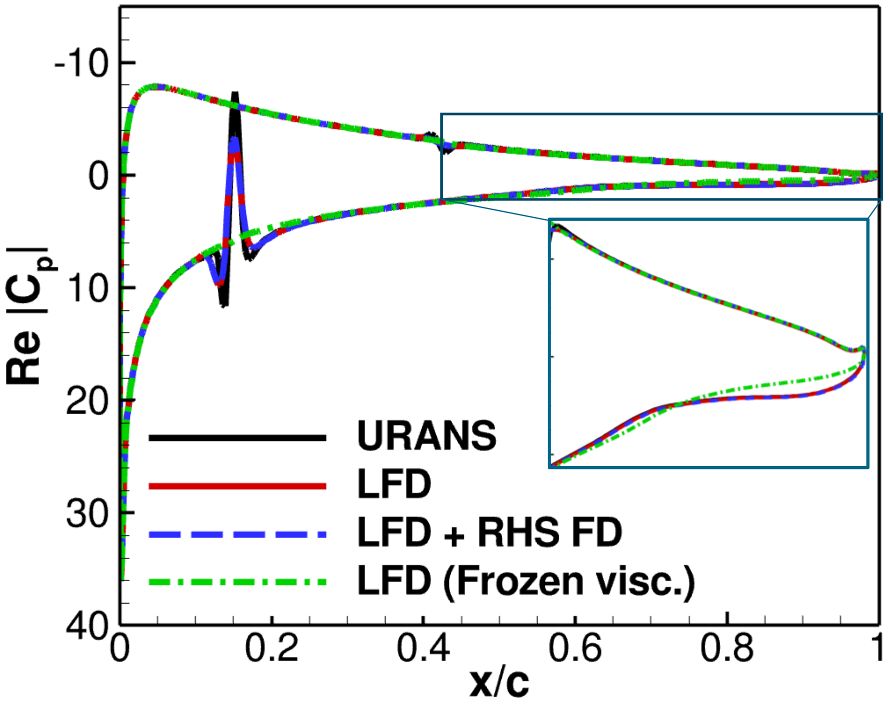


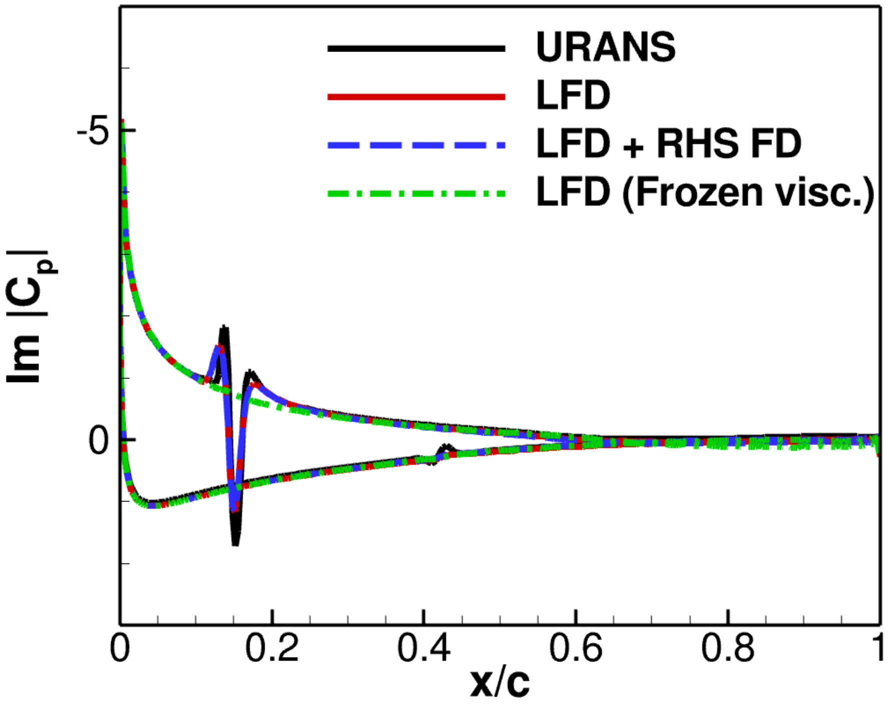


Verification
NLF(1)-0416

- First harmonic of the pressure coefficient distribution for the reduced frequency of *k* = 0.1:

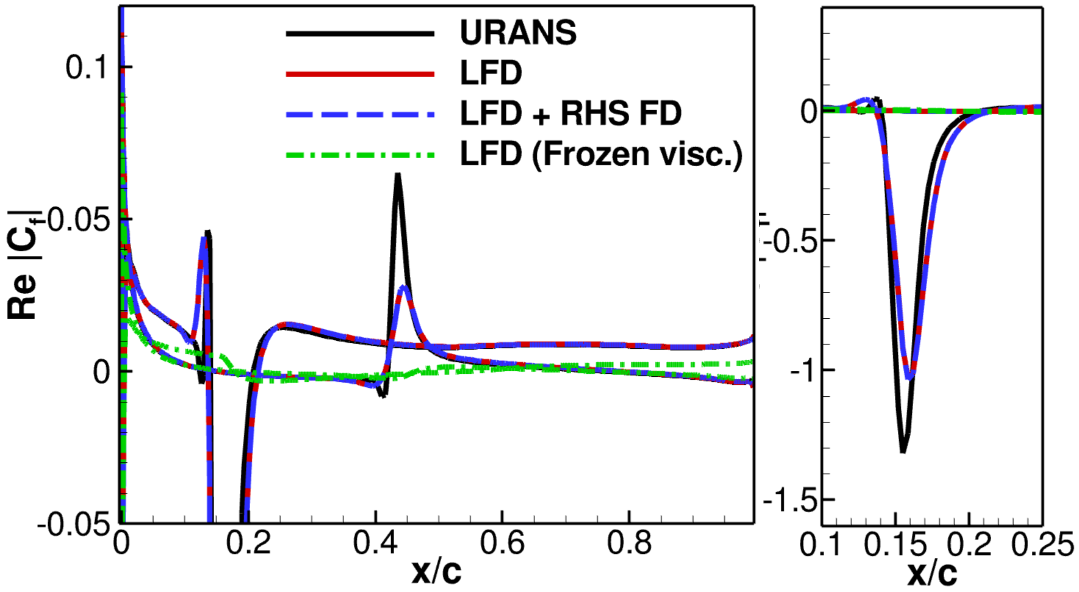


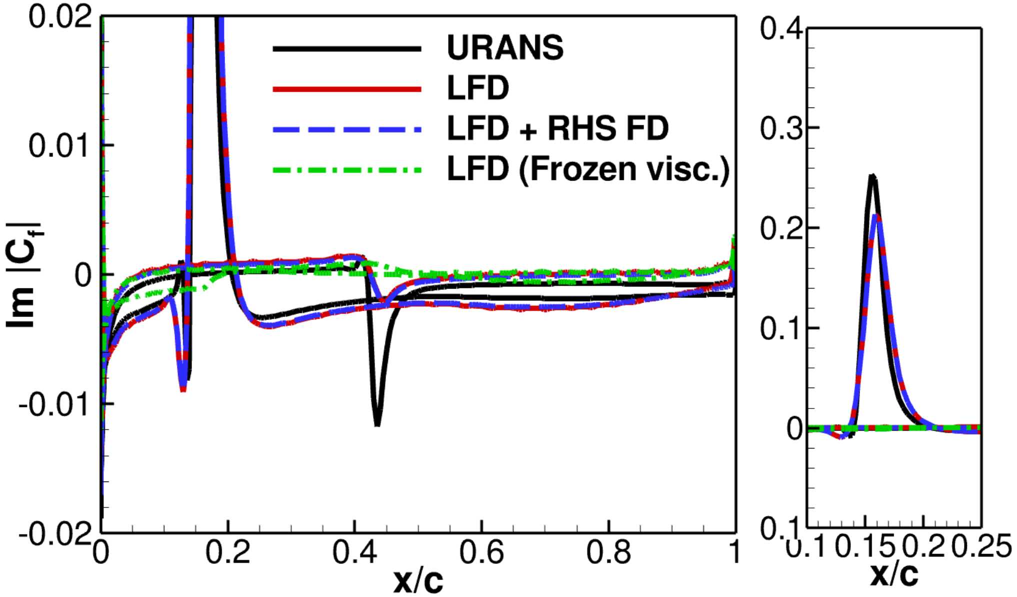




Verification
NLF(1)-0416

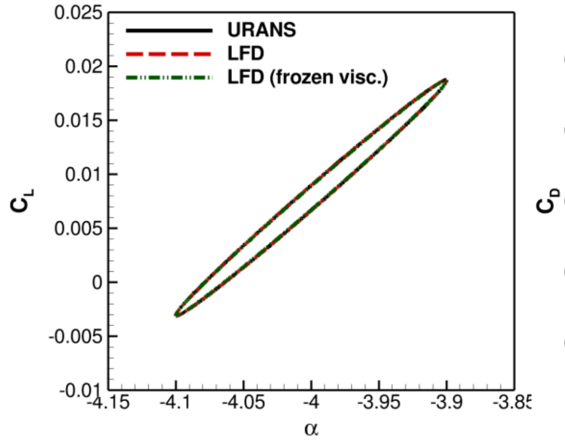
- First harmonic of the skin friction coefficient distribution for the reduced frequency of *k* = 0.1:

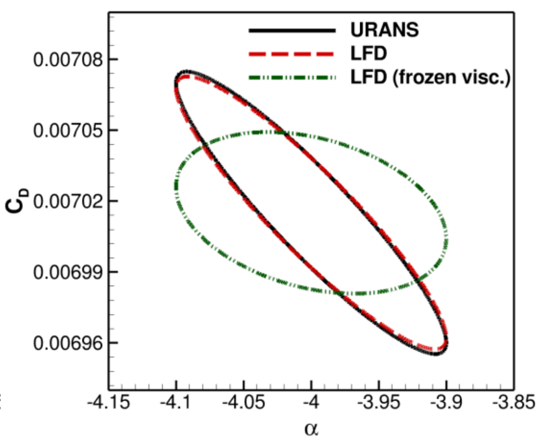


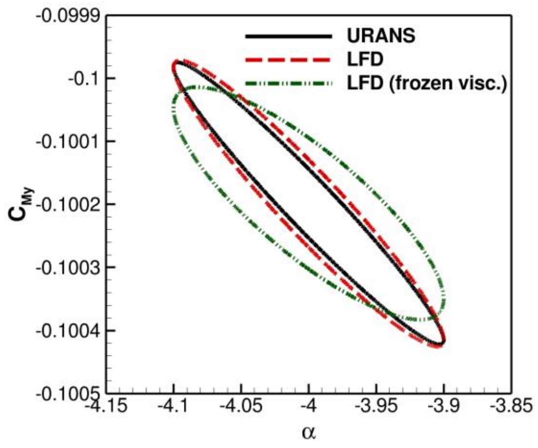


Verification
NLF(1)-0416

- Dynamic response for lift, drag, and pitching moment coefficient for a pitching motion of $\hat{\alpha} = 0.1°$ and k = 0.1:







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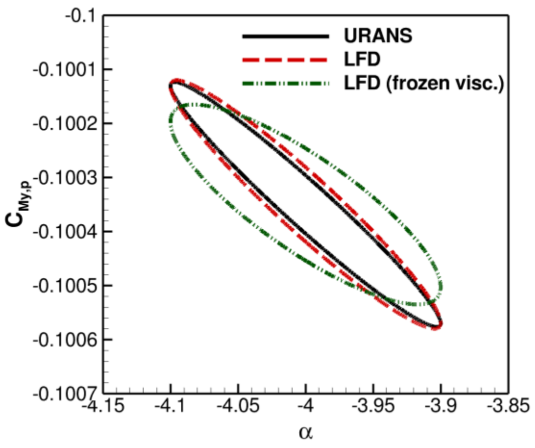

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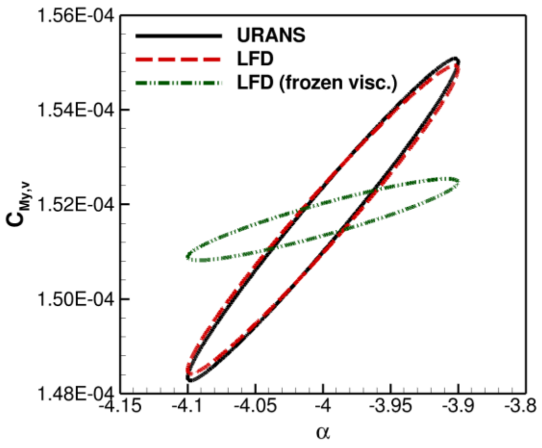

Conclusions

- The LFD solver of the DLR TAU code was extended to account for free transition effects when the transition is computed by the DLR γ model coupled to the negative S-A turbulence model.
- The LFD solver accurately predicts the unsteady aerodynamic response with respect to the reference URANS method at a considerably lower computational cost.
- Computational time is reduced in two orders of magnitude for 2D configurations (5 min. against 12 hours).
- Assuming frozen eddy viscosity (FEV) shows minor deviations in the dynamic responses of the aerodynamic loadings that mainly depend on the pressure distribution, e.g. lift, but significantly effects the dynamic response of those that highly depend on viscous effects, e. g. skin-friction, drag, and pitching moment.
- Stronger deviations are expected for the FEV approach with respect to the full-formulation of the LFD solver for detached flows or transonic configurations with shock wave.

Q&A