Mitteilung

Fachgruppe: Turbulenz und Transition

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

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Introduction:
Modern aircraft designs tend towards attaining higher cruise velocities combined with lighter and more flexible structures. This intensifies the fluid-structure interactions raising the risks of flutter. Therefore, determining the aeroelastic stability boundaries for the whole range of flight conditions at an early stage of the design process is crucial to save unnecessary costs on later modifications. Nevertheless, time-accurately solving the dynamic response to structural perturbations is prohibited in terms of computational effort, mainly due to the wide range of flight conditions that needs to be considered (e.g. Mach amplitude, altitude, load, deformation mode shape and frequency). An efficient alternative to accomplish this task is by assuming small harmonic perturbations and applying the Linear Frequency Domain (LFD) [1] method to linearly evaluate the dynamic response of the flow. The small perturbation assumption is justified on the interest of capturing the flutter onset, which will occur at infinitesimal displacements, rather than solving the flutter effect. The LFD approach was extensively verified with the DLR TAU code for fully turbulent configurations with the Spalart-Allmaras (SA) turbulence model [1,2]. However, the increased demand for cost-efficient aircraft designs and the growing awareness for global warming effects have shifted the attention back towards natural laminar aircraft designs [3]. To adapt the design capabilities of the DLR TAU code to the current demands, the LFD solver was extended to account for free transition effects when transition is predicted by the DLR γ transition transport model which was successfully integrated to the negative SA turbulence model in [4]. This work is part of the multi-disciplinary project LamTA (Laminar Tailored Aircraft) which aims to investigate the maximum potential of laminar technologies to reduce the energy consumption in flight.

Numerical Method:
The LFD method is based on the concept that under small amplitude perturbations, the RANS equations can be linearized about the steady state by using a Taylor series expansion up to its first order term. Then, the residual can be written as

$$R(W,x,\dot{x}) \approx R(\bar{W},\bar{x},\dot{\bar{x}}) + \left.\frac{\partial R}{\partial W}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \widetilde{W} + \left.\frac{\partial R}{\partial x}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \tilde{x} + \left.\frac{\partial R}{\partial \dot{x}}\right|_{\bar{W},\bar{x},\dot{\bar{x}}} \dot{\tilde{x}}.$$

Expressing the perturbations $\widetilde{W}$, $\tilde{x}$, and $\dot{\tilde{x}}$ in terms of the first harmonic of a Fourier series, $\tilde{\varphi}(t) = \hat{\varphi} e^{i\omega t}$, the governing equations get reduced to a complex linear system that reads

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

Then, splitting the amplitude of the fluctuations into their real and imaginary parts, $\widehat{W} = \mathrm{Re}\widehat{W} + i\mathrm{Im}\widehat{W}$ and $\hat{x} = \mathrm{Re}\hat{x} + i\mathrm{Im}\hat{x}$, the complex linear systems is turned in to two coupled linear systems,

$$\begin{bmatrix} \frac{\partial \mathrm{R}}{\partial W} & -\omega n \mathrm{I} \\ \omega n \mathrm{I} & \frac{\partial \mathrm{R}}{\partial W} \end{bmatrix} \widehat{W}^* = \begin{bmatrix} \frac{\partial \mathrm{R}}{\partial x} & -\omega n \frac{\partial \mathrm{R}}{\partial \dot{x}} \\ \omega n \frac{\partial \mathrm{R}}{\partial \dot{x}} & \frac{\partial \mathrm{R}}{\partial x} \end{bmatrix} \hat{x}^*,$$

where $\widehat{W}^* = [\mathrm{Re}\widehat{W} \quad \mathrm{Im}\widehat{W}]^T$ and $\hat{x}^* = [\mathrm{Re}\hat{x} \quad \mathrm{Im}\hat{x}]^T$. Given the linearization of the model, it is only valid for small perturbations of the flight and aircraft parameters, and thus non-linear effects such as shifts in frequency or harmonic modes are neglected. For the coupled γ – SAneg transition transport model $W = [\rho\, u\, v\, w\, p\, \tilde{\nu}\, \gamma]^T$ and $R = \left[R^\rho\, R^u\, R^v\, R^w\, R^p\, R^{\tilde{\nu}}\, R^\gamma\right]^T$. For further details on the implementation of the LFD method and the DLR γ transition transport model the authors refer to [1,2,4].

Results:

Figure 1 shows the first validation results for the implementation of the DLR γ model into the LFD solver of the DLR TAU code. For this purpose, a harmonic perturbation is generated on the NLF(1)-0416 airfoil at a chord-based Reynolds number of $Re_\infty = 4 \cdot 10^6$ and an incidence angle of α = -4° through a pitching oscillation around x/c = 0.25 of amplitude $\hat{\alpha}$ = 0.1° and a wide range of reduced frequencies ranging from *k* = 0.001 to *k* = 500. The left side of figure compares the lift coefficient amplitude and phase of the dynamic response obtained with the LFD solver with its time-accurate RANS counterpart for the whole range of assessed reduced frequencies, *k*, whereas the right side depicts the distributions of the real and imaginary parts of the fluctuation amplitude of the pressure coefficient for the reduced frequency of *k* = 0.2. The results show an overall nice agreement between the linearly and non-linearly resolved dynamic response of the flow.

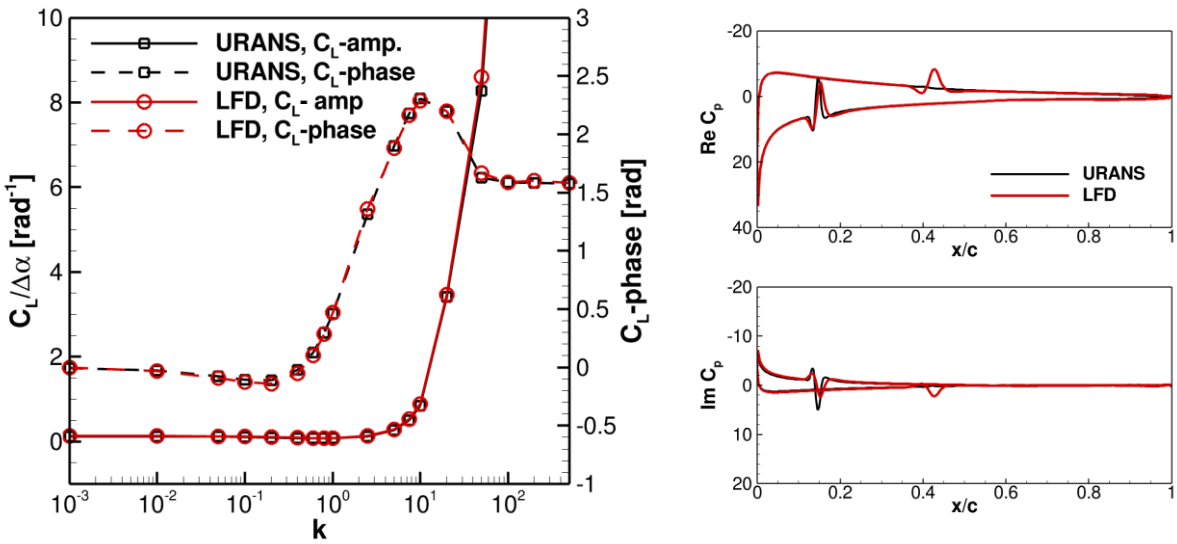

Figure 1: First harmonic lift coefficient on the NLF(1)-0416 airfoil for a pitching motion of amplitude $\hat{\alpha} = 0.1°$ as a function of the reduced frequency, $k = 2\pi f \cdot c/U_\infty$, (left), and first harmonic of the pressure coefficient distribution for the reduced frequency of $k = 0.2$ (right).

Reference:

[1] Thormann, R., Widhalm M., “Linear-Frequency-Domain Predictions of Dynamic-Response Data for Viscous Transonic Flows” AIAA Journal, Vol 51, No 11, pp:2540-2557, 2013. https://doi.org/10.2514/1.J051896

[2] Widhalm, M., Thormann, R., "Efficient Evaluation of Dynamic Response Data with a Linearized Frequency Domain Solver at Transonic Separated Flow Condition", AIAA Paper 2017-3905. 35th AIAA Applied Aerodynamics Conference, 2017. https://doi.org/10.2514/6.2017-3905

[3] Green, J. E., “Laminar Flow Control - Back to the Future?”, 38th Fluid Dynamics Conference and Exhibit, AIAA Paper 2008-3738, 2008. https://doi.org/10.2514/6.2008-3738

[4] François, D. G., Krumbein, A., “On the Coupling of a γ-based Transition Transport Model to the Negative Spalart-Allmaras Turbulence Model”, 56th 3AF International Conference on Applied Aerodynamics, FP36-AERO2022-francois, 2022.