Experience with rapid unsteady DLR-CFD-Methods

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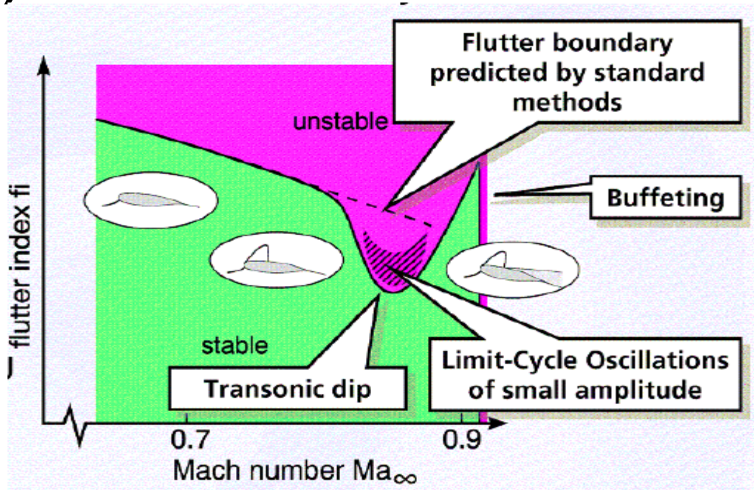
Outline

- Motivation/Introduction
- Doublet Lattice Method
- Successive Kernel Expansion Method
- Improved Successive Kernel Expansion Method
- Numeric Experiments (LANN, Goland)
- Linear Frequency Domain Solver LFD-TAU
- Numeric Experiments
- Conclusion and Outlook

Motivation

- For flutter analysis of a new aircraft many calculations are necessary due to the large parameter space
  - 1-7 Mach numbers
  - 5-12 frequencies
  - 40-150 mode shapes
  - different loading and fueling: 15-20
  - flight attitude (elastic, trimmed): 1-3
- more than 1 Mio. cases and 1 URANS simulation lasts about 27h on 32 CPU (clean wing with fuselage, 5.4 Mio Points)
- Reduction of computational costs
  - different CFD Methods for different flight conditions
  - correction of DLM with CFD
  - Linear CFD Methods
  - POD



Doublet Lattice Method

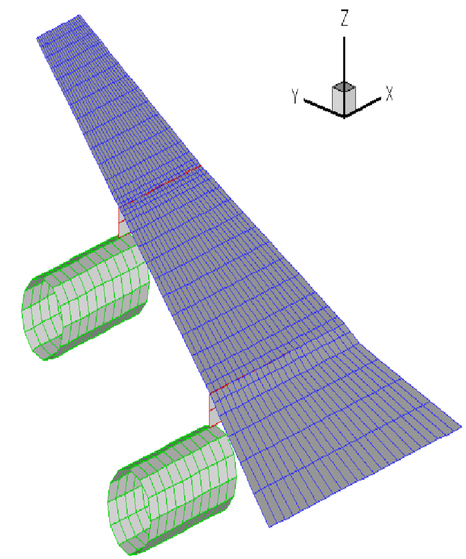
- Panel Method for unsteady, subsonic flow
  - compressiblity via isentropy
  - no profiles and no mean angle of attack
  - small perturbations compared to the free-stream velocity
  - no inplane modes
- integral equation

$$w = \frac{1}{8\pi} \iint_A \Delta c_p K(x-\xi, y-\eta, 0)\, d\xi\, d\eta$$

- in discretized form:

$$w = AIC\, \Delta c_p,$$

where $AIC(i,j)$ decribes the influence of box i to box j



Sample Doublet Lattice Grird

- **upwind w describes the z velocity of the motion in the frequency domain**

$$
\begin{aligned}
w\, e^{j\omega t} &:= \frac{1}{U_\infty}\frac{d}{dt}dz \\
&= \frac{1}{U_\infty}\frac{d}{dt}\left\{h_0 + \alpha_0(x - x_{ref}\right\} e^{j\omega t} \\
w &= \frac{1}{U_\infty} i\omega \left\{h_0 + \alpha_0(x - x_{ref})\right\} + \alpha_0 \underbrace{\frac{dx}{dt}}_{=U_\infty} \\
&= \alpha_0 + i\omega^* \left\{\frac{h_0}{c_{ref}} + \alpha_0 \frac{x - x_{ref}}{c_{ref}}\right\}
\end{aligned}
$$

- **Influence matrix Q:** $Q_{i,j} = q_\infty \Phi^i \sum_k \Delta cp_k^j S_k = q_\infty \Phi^i AIC^{-1} w^j\, S$
  with $S = diag(S_k)$**,** S_k **for panel area**

Successive Kernel Expansion Method

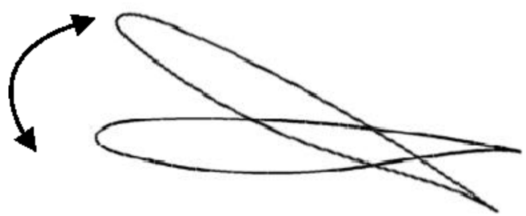
- in "Transonic AIC Weighting Method using Successive Kernel Expansion" von Shen, Silva und Liu following method is outlined:
- terms of $w = \frac{1}{8\pi} \iint\limits_A \triangle c_p K(x-\xi, y-\eta, 0)\, d\xi\, d\eta$ are expanded as taylor series
- Correction of the quasi-steady, zeroth terms via the difference of two steady CFD-results at different deformation states, e.g. at mean and maximum deflection
- considering the k-th taylor coefficient:

$$w^{(k)} = \frac{1}{8\pi} \iint\limits_A \sum_{j=0}^{k} \triangle c_p^{(j)} K^{(k-j)}(x-\xi, y-\eta, 0)\, d\xi \;\; d\eta, k = 0, 1$$

- with the same steps as in the DLM:

$$w^{(k)} = \sum_{j=0}^{k} AIC^{(j)}\, \triangle c_p^{(k-j)}$$

- This convolution sum is solved successively for $\triangle cp^{(k)}$



- the zeroth element of the taylor series describes the quasi steady part. which will be corrected via CFD results:

$$w^{(0)} = AIC^{(0)}\,\triangle c_p^{(0)} \text{ (Doublet Lattice Theorie)}$$
$$= C\,AIC^{(0)}\,\triangle c_p^{(0),\,given}$$
$$\triangle c_p^{(0),\,given} = \frac{\triangle c_p^{CFD}(\alpha_1) - \triangle c_p^{CFD}(\alpha_2)}{\alpha_1 - \alpha_2}$$

  with C as correction matrix
- extension of SKEM for user-defined order of the taylor series and analysis of convergence properties led to

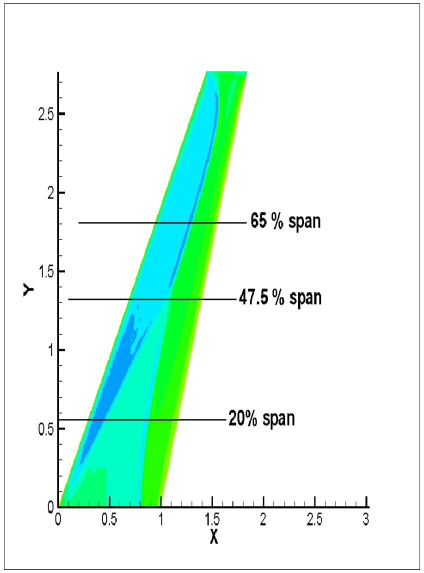
iSKEM - improved SKEM

- difference:

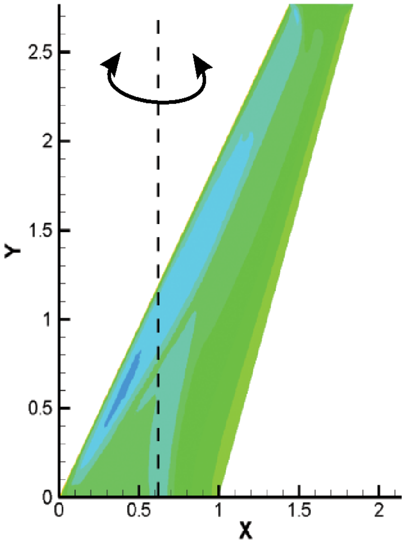
$$\underline{\text{AIC}} = C\,AIC^{(0)} + \sum_{k=1}^{N-1} (i\omega^*)^k * AIC^{(k)}$$
$$w = \underline{\text{AIC}}\triangle cp$$

Numeric Experiments

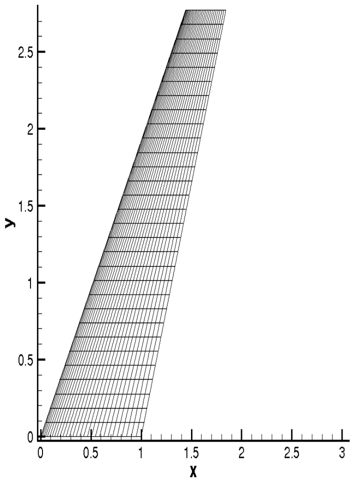
- geometry: LANN-Wing
- Euler simulations for ω^* = 0.1, 0.5, 1.0
- RANS simulations with mean angle of attack α_0 = 0.6 and 2.6



c_p-contour Euler



c_p-contour RANS

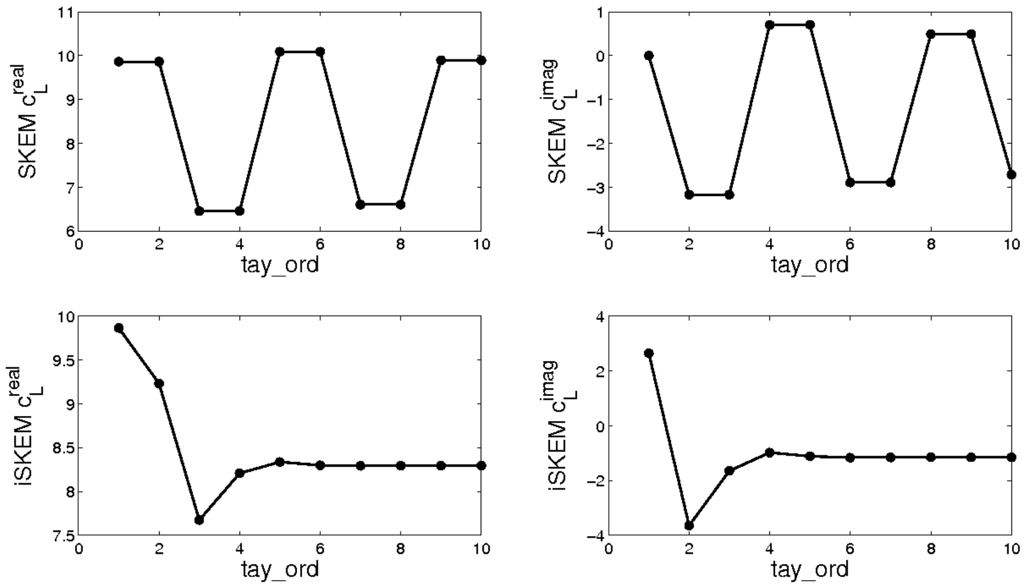


DLM-Grid

Convergence of taylor series

SKEM

iSKEM



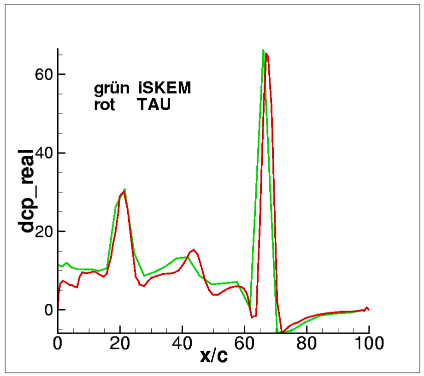
Reihenkonvergenz bei $\omega^* = 0.5$

- **SKEM converges only for small reduced frequencies because it expands, in constrast to iSKEM, the inverse AIC-matrix**
- **iSKEM converges for any reduced frequency**

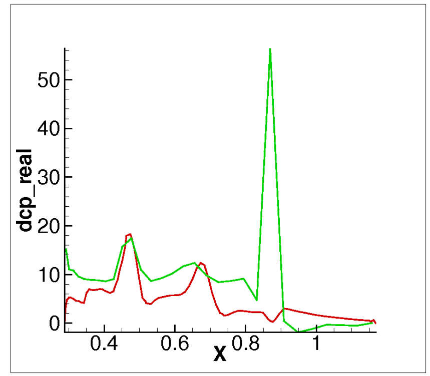
Comparison with inviscid flow (TAU Euler)

cut at 20% span width, 10 elements in taylor series

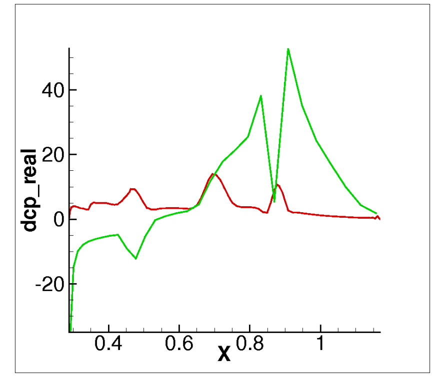
$M_\infty = 0.82$, $\alpha_0 = 0.6°$, $\tilde{\alpha} = 0.2°$ **TAU** **iSKEM**



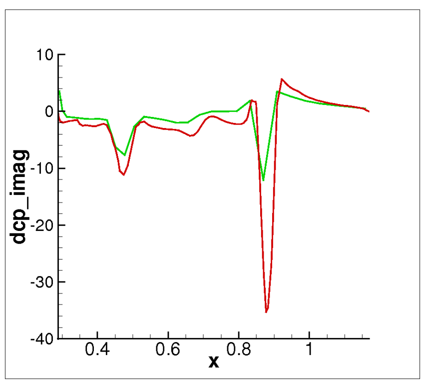
$\omega^* = 0.1$



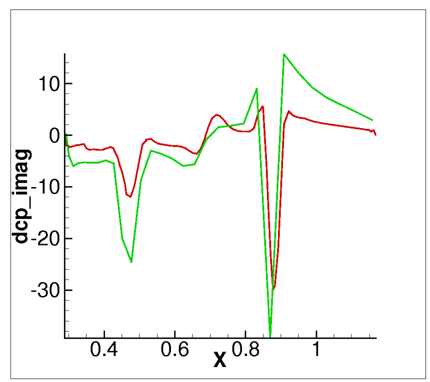
$\omega^* = 0.5$



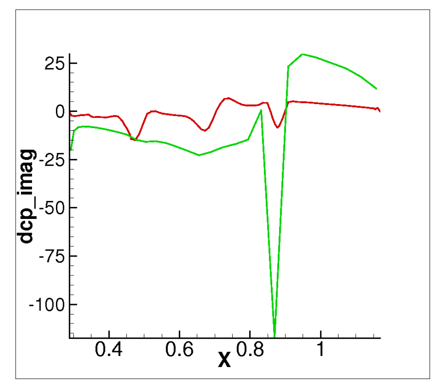
$\omega^* = 1.0$



$\omega^* = 0.1$



$\omega^* = 0.5$

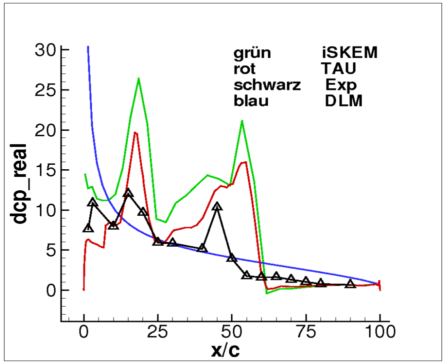


$\omega^* = 1.0$

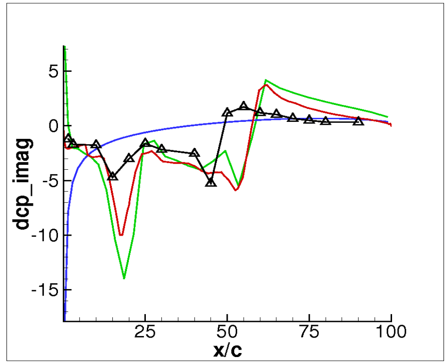
Comparison with viscous flow

$Ma = 0.82, \omega^* = 0.2, Aoa = 0.6^\circ/2.6^\circ$ **TAU** **iSKEM** **DLM** **EXP**

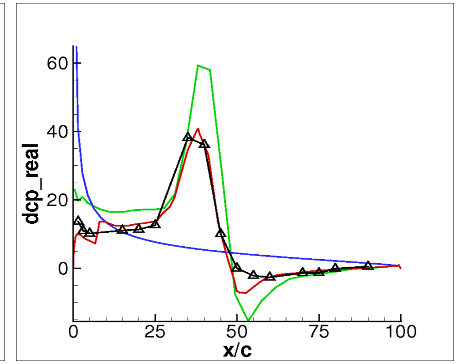
attached



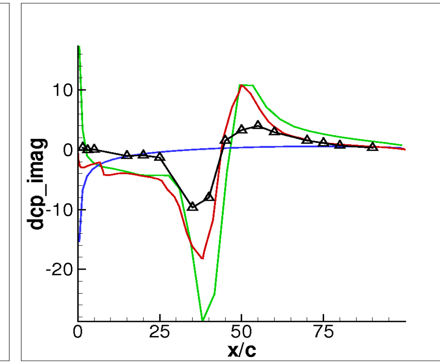
re(cp)ct5 20% span



im(cp)ct5 20% span

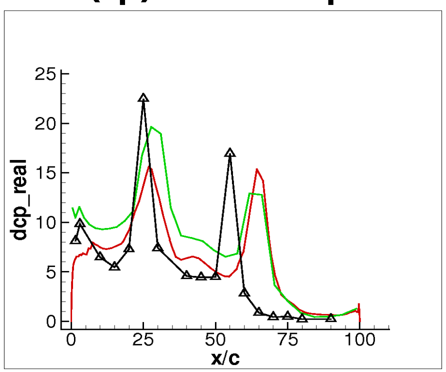


re(cp)ct5 65%span

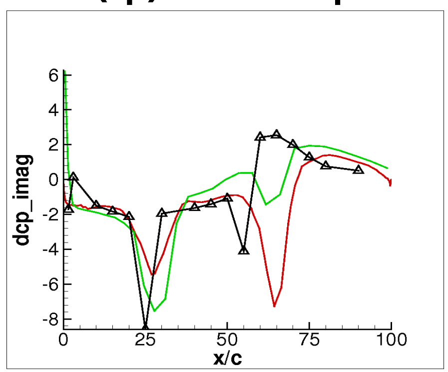


im(cp) ct5 65% span

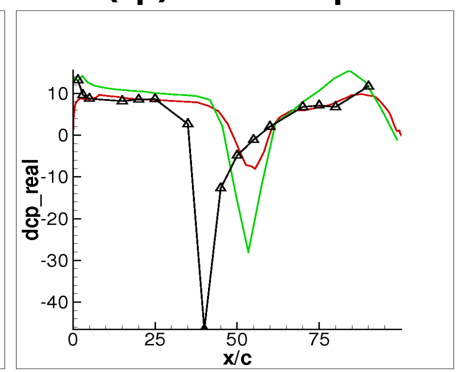
separated



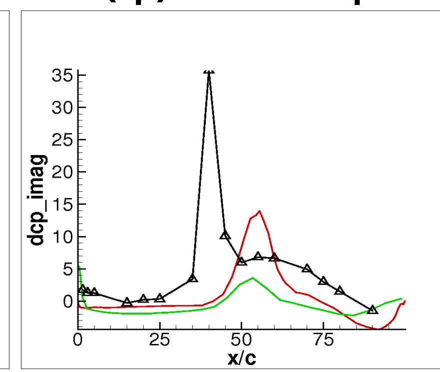
re(cp)ct9 20% span



im(cp)ct9 20% span



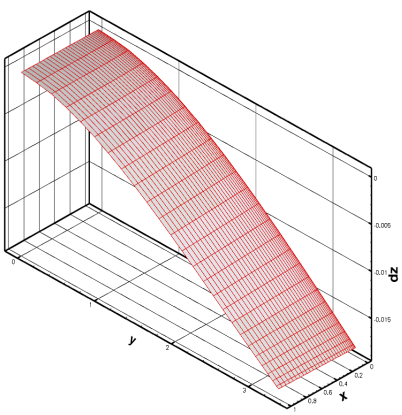
re(cp)ct9 65%span



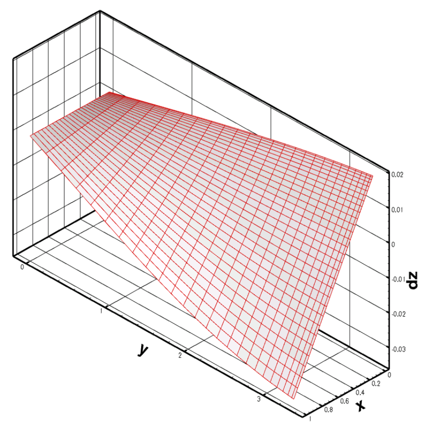
im(cp) ct9 65% span

Testcase Goland Wing

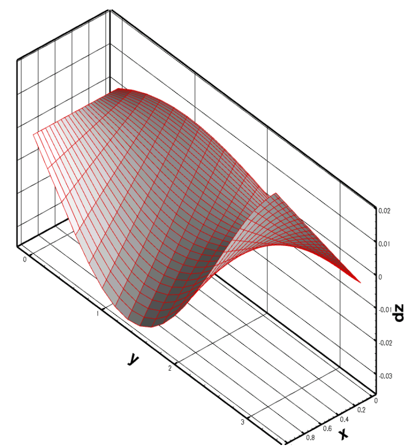
- in cooperation with Uni Liverpool (Sebastian Timme)
- rectangular wing with a constant cross section defined by a 4% thick parabolic-arc aerofoil
- comparison of GAFs Q dependent on $Ma \in [0.4, 0.95]$ and $\omega^* \in [0, 0.5]$
- preliminary results



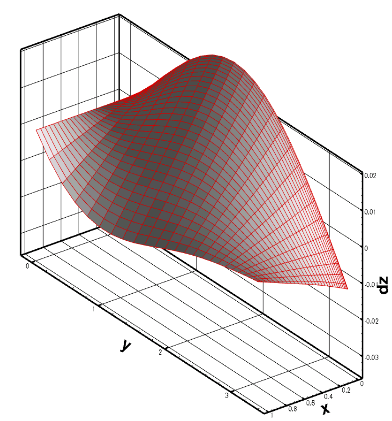
mode 1



mode 2

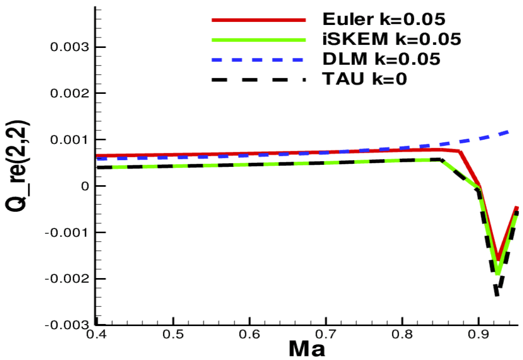


mode 3

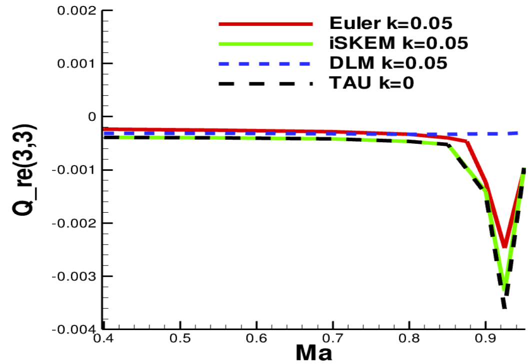


mode 4

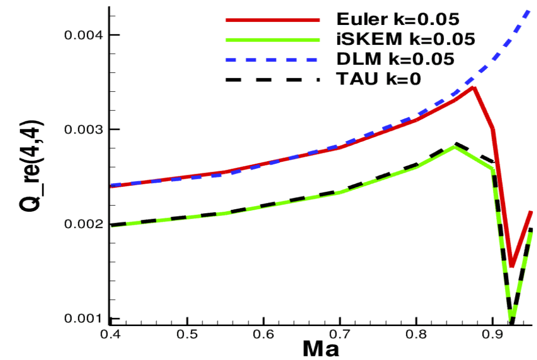
GAFs for $\omega^* = 0.05$



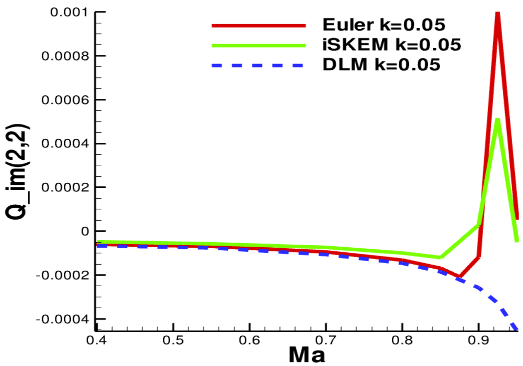
real Q_{22}



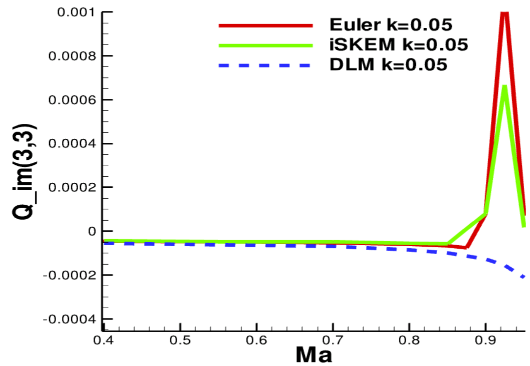
real Q_{33}



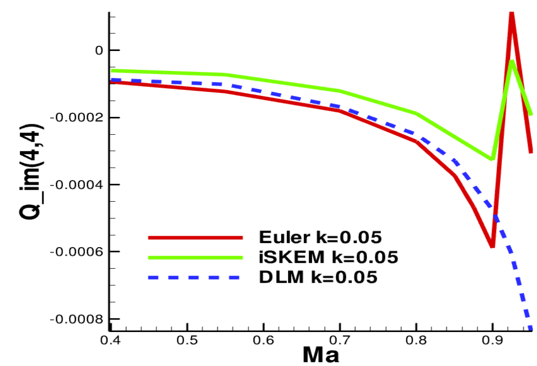
real Q_{44}



imag Q_{22}

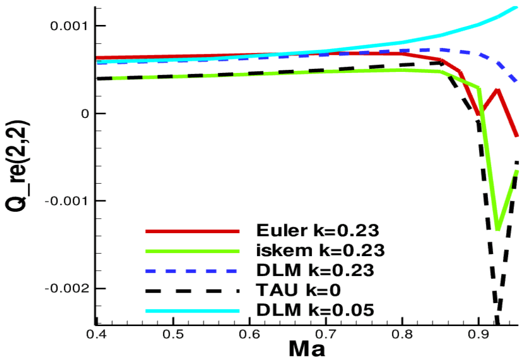


imag Q_{33}

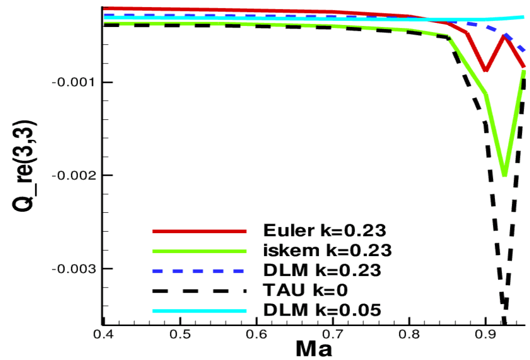


imag Q_{44}

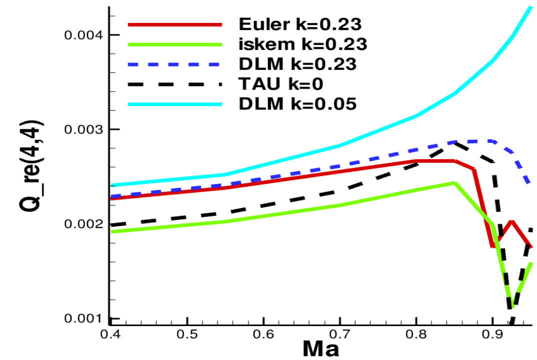
GAFs for $\omega^* = 0.23$



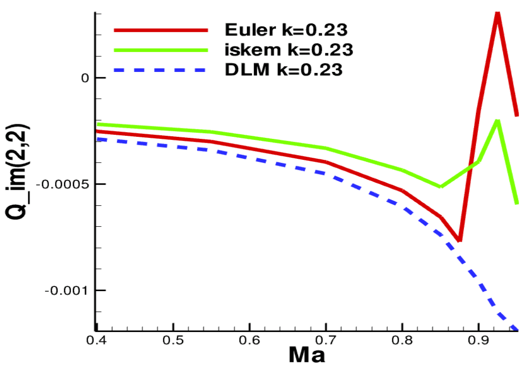
real Q_{22}



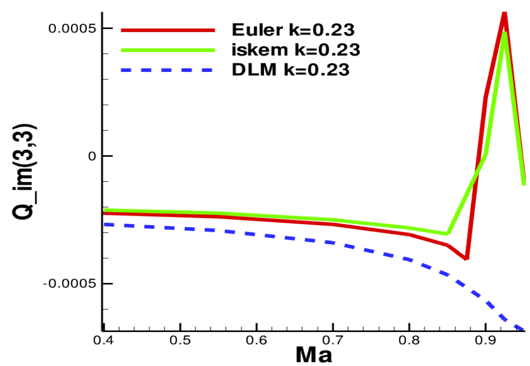
real Q_{33}



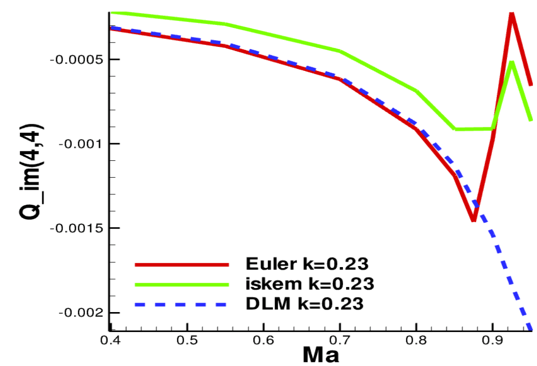
real Q_{44}



imag Q_{22}

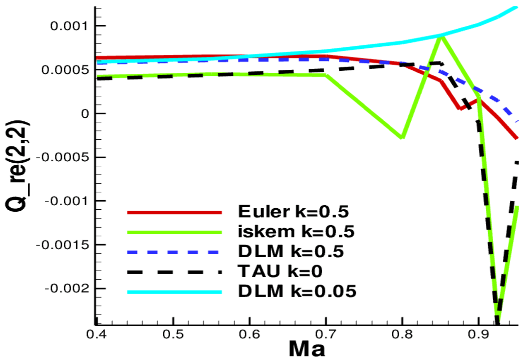


imag Q_{33}

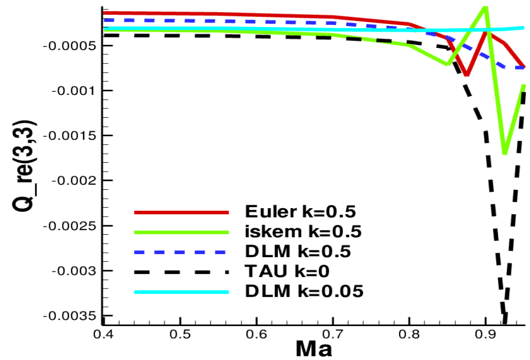


imag Q_{44}

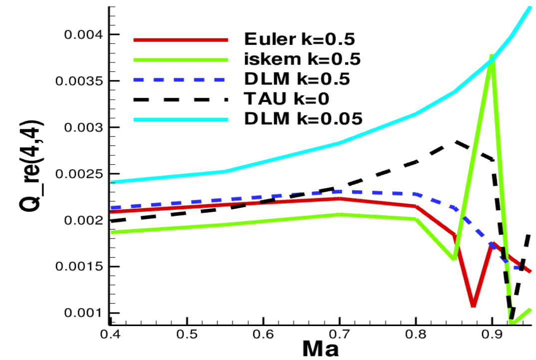
GAFs for $\omega^* = 0.5$



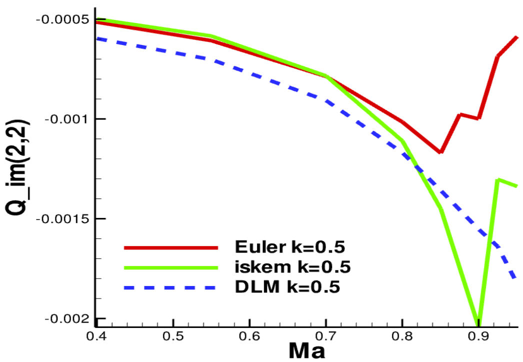
real Q_{22}



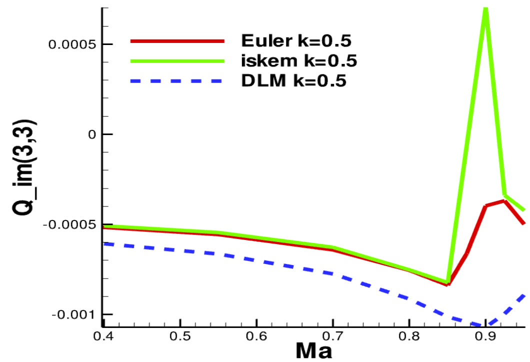
real Q_{33}



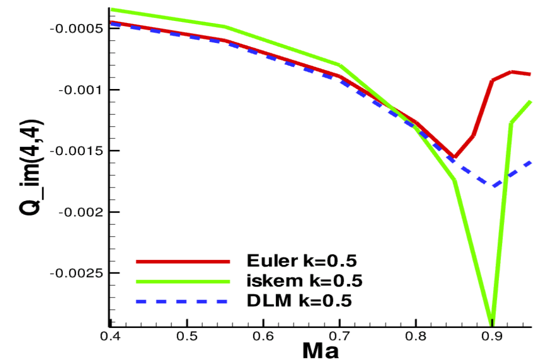
real Q_{44}



imag Q_{22}



imag Q_{33}



imag Q_{44}

Linear Frequency Domain Solver (LFD TAU)

- **development in cooperation with DLR-AS (Markus Widhalm)**
- **linearization of**

$$\frac{dU}{dt} + R(U, x, \dot{x}) = 0$$

about the steady point $\overline{U}$ leads to

$$\frac{d\tilde{U}}{dt} + \frac{dR}{dU}(\overline{U}, \overline{x}, 0)\tilde{U} + \frac{dR}{dx}(\overline{U}, \overline{x}, 0)\tilde{x} + \frac{dR}{d\dot{x}}(\overline{U}, \overline{x}, 0)\tilde{\dot{x}} = 0$$

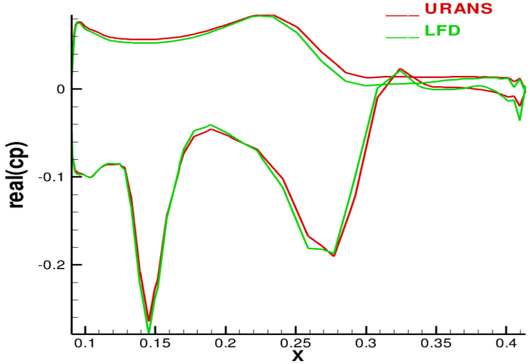
- **assuming $\tilde{U}$ and $\tilde{x}$ are harmonic:**

$$\left[j\omega I + \frac{dR}{dU} \right] \tilde{U} = - \left[j\omega \frac{dR}{d\dot{x}} + \frac{dR}{dx} \right] \tilde{x}$$

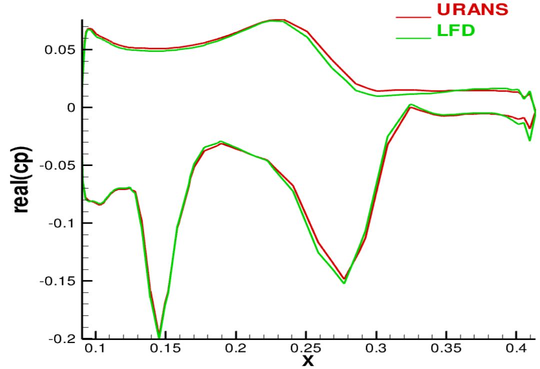
- **the complex linear system is solved as a real, double sized system with GMRes**
- **the right-hand-side is computed with finite differences and grid deformation**

Local unsteady cp distribution 20% span

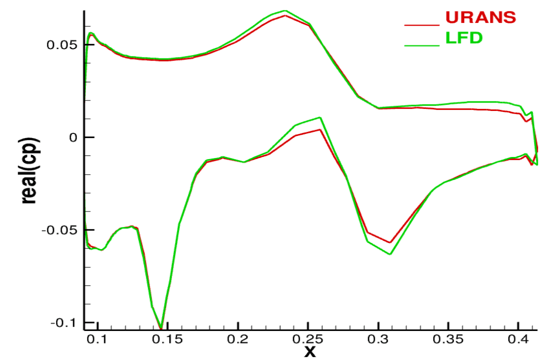
LANN Wing, $Ma = 0.82$, $AoA = 0.6°$, rigid pitch, viscous



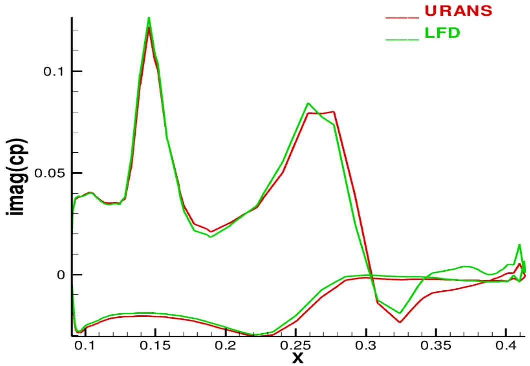
re(cp) k=0.2 20% span



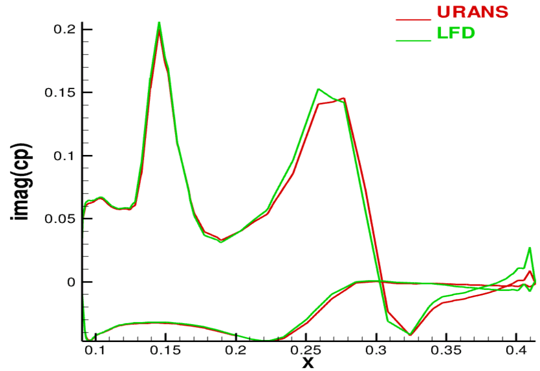
re(cp) k=0.5 20% span



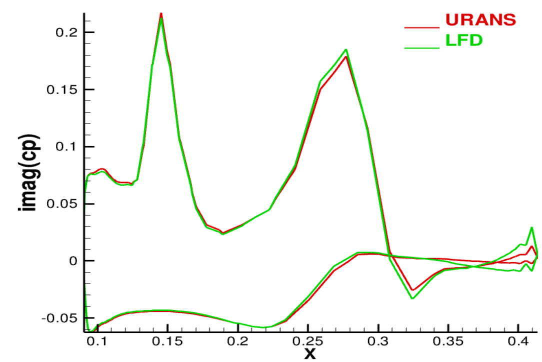
re(cp) k=1.0 20% span



im(cp) k=0.2 20% span

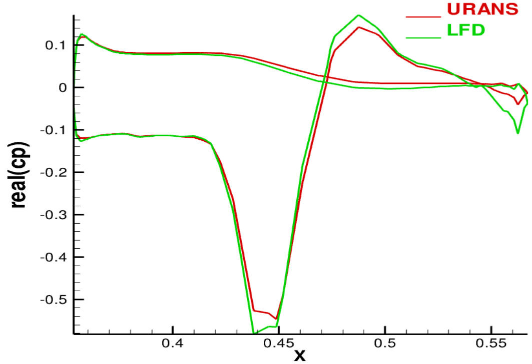


im(cp) k=0.5 20% span

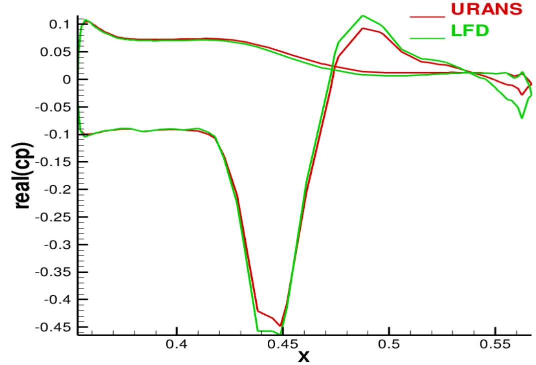


im(cp) k=1.0 20% span

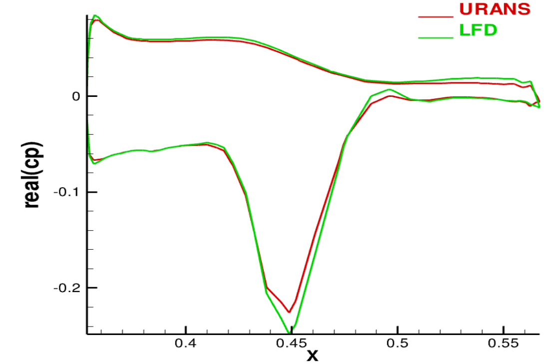
Local unsteady cp distribution 65% span



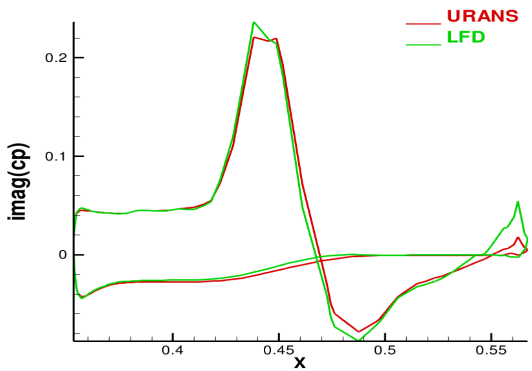
re(cp) k=0.2 65% span



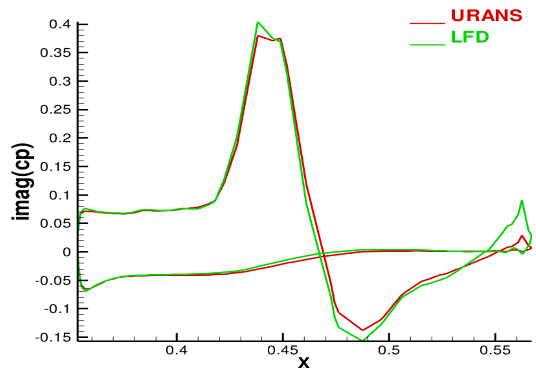
re(cp) k=0.5 65% span



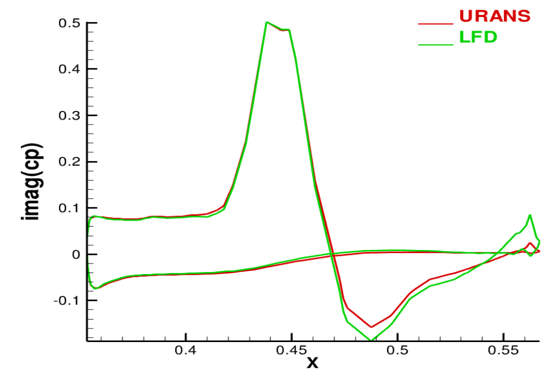
re(cp) k=1.0 65% span



im(cp) k=0.2 65% span



im(cp) k=0.5 65% span



im(cp) k=1.0 65% span

Conclusion

viscous LFD:

- for small amplitudes and medium shock-strength good agreement with URANS results
- time saving with a factor of 10-20 compared to nonlinear URANS simulations
- improved convergence with GMRes, also in shock-induced, seperated flows
- *but:* for stronger shocks and seperated flow wrong results

iSKEM:

- good agreement for torsion modes with small reduced frequencies
- even global trend for seperated flow is good
- because only quasi-steady correction, only real part and not the imag. part is corrected
- additionally only torsion part can be corrected

Outlook

viscous LFD:

- analysis of the linearisation of turbulence model with respect to strong shocks
- comparison of flutter curves
- scalability for improved parallel behaviour

iSKEM:

- grid study of CFD and DLM for Goland Wing
- comparison of flutter curves for Goland Wing
- extension for unsteady correction factors, e.g. from a LFD simulation
- extension for complex geometries (pylons, nacelles, ...)
- apply iSKEM on a Surface Panel Method