Results from ZHAW

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Outline

1. Summary of work done
   - Preliminary work
   - Test Case 1
   - Test Case 2
   - Test Case 3A
   - Test Case 3B
   - Test Case 3C?
2. RANS–LES hybrid turbulence modelling in aeroelastic problems
3. SU2 in aeroelastic problems
4. Open issues

Summary of work done

- All test cases with Edge, in particular for Case 3, run with non-linear URANS models (k-ω EARSM) and RANS-LES hybrid approach,
- Test Cases 1 and 3B also with SU2 (motivation: open-source software, aeroelastic module soon in the main distribution, implicit Euler).

Settings

Edge	SU2
64 - 512 CPU	64 - 1024 CPU
workshop cgns grids	workshop cgns grids
coarse, medium, fine	coarse, medium
JST for TC 1 and 2, Roe for TC 3	Roe
Dual time stepping, RK3+MG	Dual time stepping, implicit Euler (MG)
EARSM, k-ω, SA, DDES (SA)	SA (TC 1), SST (TC 3)
$\Delta t = [10^{-3}s - 10^{-4}s]$	$\Delta t = [10^{-3}s - 10^{-4}s]$
Rigid grid deformation and linear combination of pre-deformed grids, respectively	N/A
Over 10 periods	over 10 periods
steady state: over 5 orders of magnitude residuals reduction	over 5 orders of magnitude residuals reduction

Preliminary work

- Generation of indicial function via CFD (Edge, SU2) for various configurations (AIAA-2015-3170),
- Assessment of sensitivity to the “usual” parameters such as Δt, number of subiterations, turbulence model, etc against analytical solutions (Wagner, Küssner function in incompressible regime),
- Good agreement in general, provided grid quality is acceptable.

Generation of indicial functions

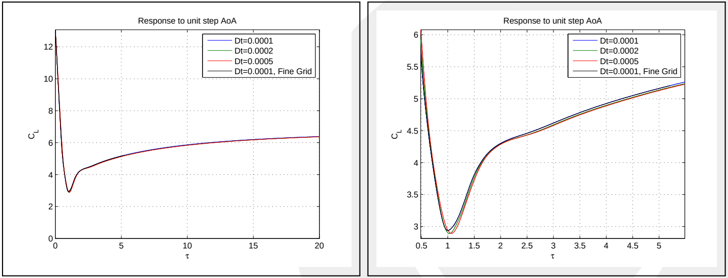


Figure 1: Effect of time step and grid resolution: NACA0006 aerofoil lift due to a unit step in the angle of attack for $M = 0.3$.

NACA0006, AoA response

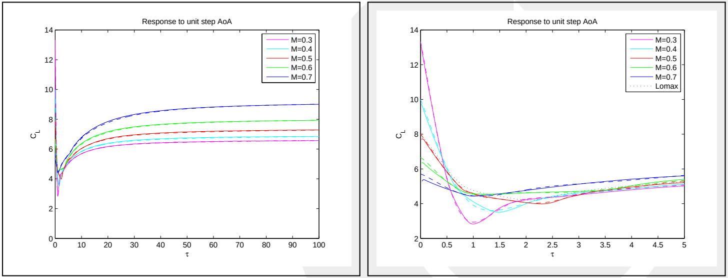
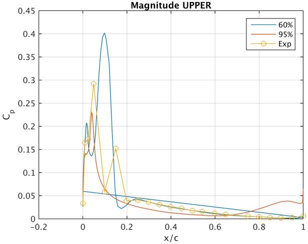


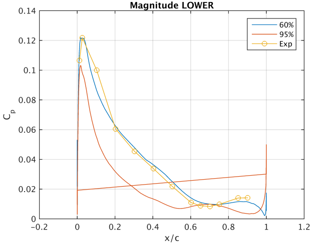
Figure 2: NACA0006 lift coefficient in the transitory region RANS

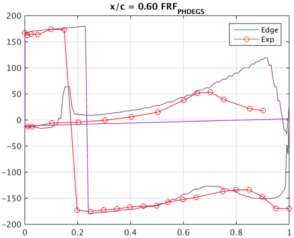
Test Case 1

- No simulation is in agreement with the “Sensor 5”,
- Good agreement between Edge and SU2,
- No significant difference between coarse and medium grid,
- No significant difference between different turbulence models (URANS),
- No significant role played by time step length,
- No significant difference with / without fixed transition,
- Amplitude of higher harmonics NOT negligible.

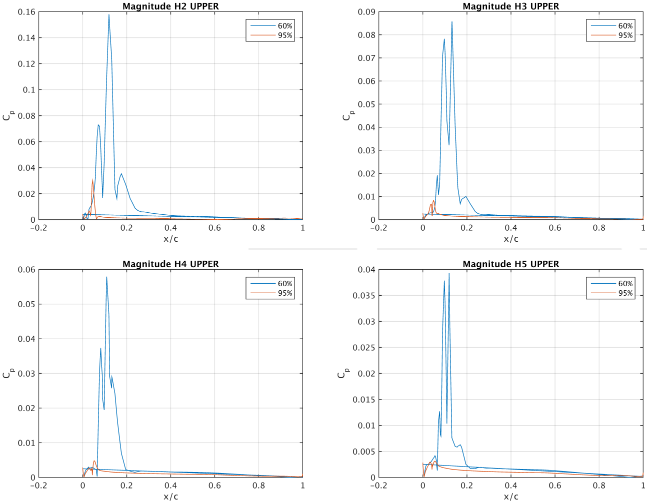
Test Case 1 - SU2







Test Case 1 - Higher harmonics



Test Case 2 - Codes/Settings

- SU2 not used in this case,
- In order to improve speed on my small cluster, Edge is used with the “old” grid deformation approach, based on a linear combination of pre-deformed grids.

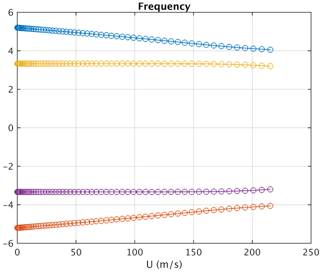
Test Case 2 - Process

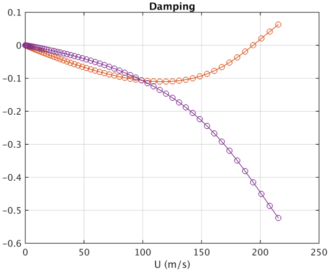
- Pitch and plunge degrees of freedom are “freed” after a steady state solution is reached,
- At the start of the unsteady solution, the wing is not in equilibrium: oscillations with “significant” amplitude appear immediately,
- Analysis of the oscillations: frequencies, damping ratios, modeshapes. However, I could not separate them with fft in this test case (but I have in Test Case 3C).
- Assessment of dynamic pressure for the next simulation, and start over,
- The analysis performed with a (very simple) ROM provides a much clearer picture.

Test Case 2 - Results

- Flutter speed unsurprisingly depends on spatial and temporal resolution, i.e. grid, Δt and turbulence model (i.e. everything that may introduce damping),
- Results obtained with coarse grid show a far too high flutter dynamic pressure, medium grid improves only marginally,
- Simulations seem to be significantly affected by small changes in parameters such as time step length (it converges for $\Delta t \simeq 10^{-4}s$, spatial resolution and turbulence model,

Test Case 2 - Results





Unstable mode:

$$\left\{ \begin{array}{c} \theta \\ h \end{array} \right\} = \left\{ \begin{array}{c} -0.0001 - 0.0288i \\ -0.0060 + 0.0242i \end{array} \right\}$$

frequency $\simeq 4.17\, Hz$. Flutter speed $\simeq 194 psf$.

Question

- Let us assume that we can generate an accurate, linear ROM in the frequency domain:

$$(M + M_A)\ddot{q} + (C + C_A)\dot{q} + (K + K_A)q = 0,$$

  where q is the vector of the degrees of freedom (pitch, plunge),
- if the reduced frequency is low, then:

$$M_A \simeq 0, \qquad K_A \simeq \begin{bmatrix} k_{11} & 0 \\ k_{12} & 0 \end{bmatrix}, \qquad C_A \simeq \begin{bmatrix} c_{11} & c_{12} \\ c_{12} & c_{22} \end{bmatrix}$$

- Term c_{11} plays a critical role in making the system unstable. Which is the most efficient way to assess c_{11}?

Test Case 3A

- The “dominant” aerodynamic mode (shock-buffeting?) is captured by both URANS and DDES on coarse and medium grids,
- The “main” frequency is similar in all cases but the modeshape is not,
- DDES results are grid dependent, show a much richer spectrum and allow the observation of turbulent structures (movies),

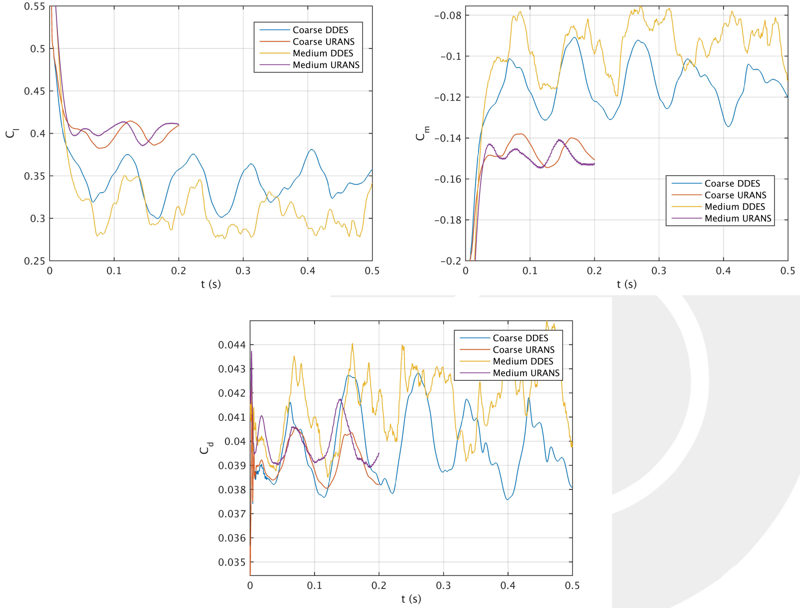


Figure 3: Aerodynamic coefficients identifying a clear oscillation of the circulation

Test Case 3B

- Same process followed in Test Case 1, with two different turbulence modelling techniques,
- (Also valid for 3C) Results are much more sensitive to all simulations parameters, and to turbulence modelling, since they directly affect shock positioning, which strongly affects unsteady forces,
- All in all, I would tend to say that DDES simulations provide a better agreement, although longer simulation times are probably necessary,
- Steady state (so to speak) is perhaps not critically important, since the unsteady part re-positions the shock,
- Higher harmonics are much lower in this case, unlike in Test Case 1,

Test Case 3B: URANS / DDES

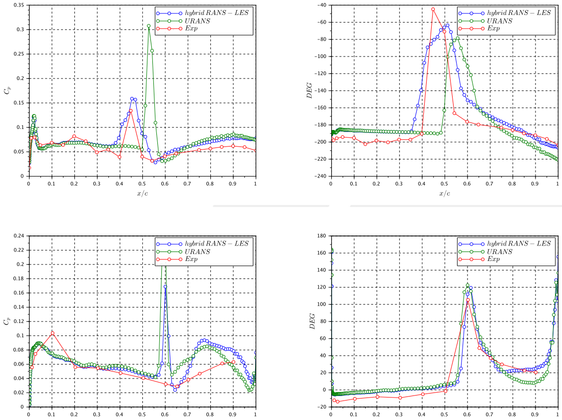
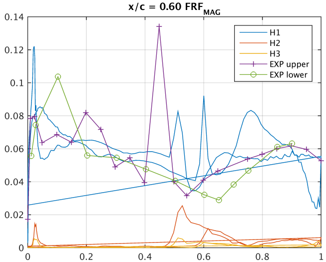
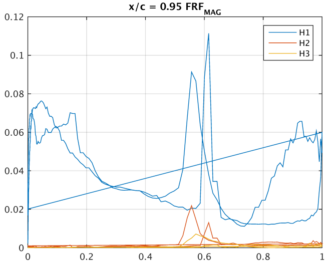


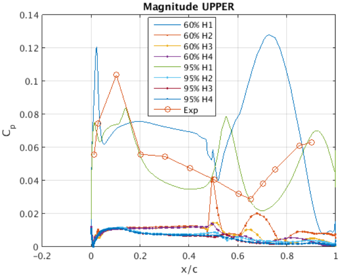
Figure 4: Test Case 3B, c_p, upper (top row) and lower (bottom row) side of the wing, $x/c = 0.60$.

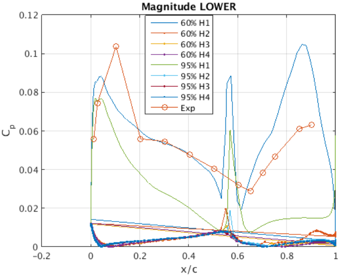
Test Case 3B: higher harmonics (Edge, DDES)





Test Case 3B: higher harmonics (SU2, SST)





Example Case 3C

- I have tried to follow the same process as in Test Case 2,
- However, analysis of oscillations is not trivial:
  - Richer spectrum, longer observation time,
  - Response depends on oscillations amplitude (both pitch and plunge), i.e. the coupled simulation may be “attracted” by the LCO, so prediction of the “linear” instability might be tricky,
- Linearisation of aerodynamics into a (very simple) ROM also is a challenging process, since the imaginary component of $\partial M/\partial\theta$ is strongly dependent on simulation settings; i.e. the problem can be solved via a proper generation of a non-linear ROM.

Test Case 3C, frequencies

All solutions predict separate frequencies at experimental conditions:

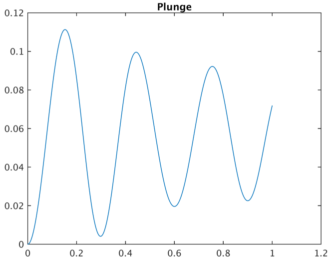


Figure 5: Edge / DDES solution

Test Case 3C, damping, flutter speed

More simulations with longer observation times are probably necessary:

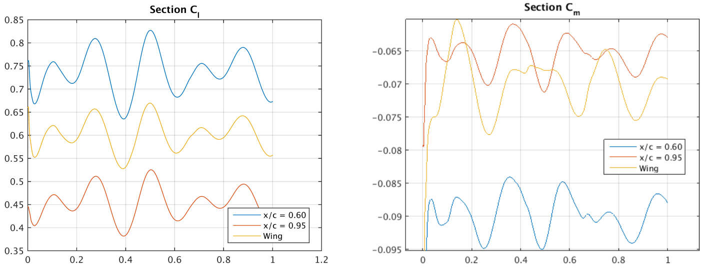


Figure 6: Edge / DDES solution

Test Case 3C, flutter speed via ROM

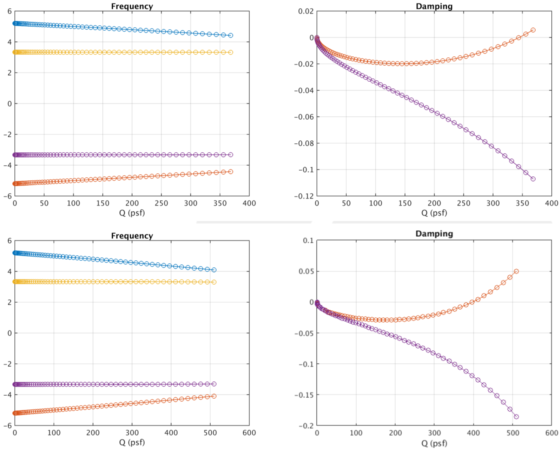


Figure 7: Examples of solution for Test Case 3C via ROM, small changes in parameters affect flutter speed more than proportionally.

RANS–LES hybrid turbulence modelling in aeroelastic problems

Pros

- Higher accuracy – or physical consistence – in predicting large, anisotropic, unsteady turbulent structures,
- It reduces, in particular, the detrimental “damping” generated by the RANS stress tensor in unsteady flow,

Cons

- Introduces a strong dependence on spatial and temporal resolution,
- Generates a richer spectrum which might require longer observation times,
- It requires adequate Δt,

SU2 for aeroelastic problems

Pros

- Open-source,
- Fairly robust and mature,
- Easy to “customize” and/or couple to other codes,
- Krylov solver (implicit Euler),
- Pre-processing is parallel to a large extent,
- Excellent scalability (checked up to a few thousands CPUs),
- Aeroelastic “module” developed for high flexibility (e.g. coupling with external structural solvers).

Cons

- Performance (speed) strongly dependent on the problem / grid,
- Limited turbulence models portfolio,
- Validation level not yet comparable with the best known codes, e.g. the ones used in this workshop + TAU, EISA, . . .

Open issues

- Costs of simulations,
- Costs of post-processing,
- Comparison of these costs with “simpler” methods, ROM, flight testing?,
- What should / could be done with the wealth of information generated by CFD analysis?
- Hybrid modelling, which additional guidelines are necessary? (Statistics of resolved turbulence, absence of grid induced effects)
- Hybrid modelling, which approach? which model?

References I

Shaping the Future of Aerospace