German Aerospace Center (DLR)

Eighteen Month Review Meeting
24th - 25th November 2016, DLR - Göttingen

Presented by M. Ripepi / J. Nitzsche
WP 2 - Understanding Non-linearities in CFD Based Gust Simulations (lead by ULIV)

Task T2.1 Non-linear Aerodynamics of Gust Using RANS Comparison of highly accurate and simplified methods

Subtask T2.1.1
- Comparison of highly accurate methods resolving gusts in the flow field and simplified field velocity approach on 2D and 3D test cases, different gust wave lengths
- D2.2 – “Initial report on the prediction of non-linear behaviour using Boundary Condition methods” was delivered III/2016
WP 2 - Understanding Non-linearities in CFD Based Gust Simulations (lead by ULIV)

Task T2.4 Non-linear Structural Response to Gusts

Subtask T2.4.1
- D2.5 – “Report on coupling with full order geometrically non-linear finite-element structural models” was delivered II/2016
  - NASTRAN analysis of generic wing
  - Initial study: linearised approach
  - “Preloaded modal analysis”
    - 1st torsion increases slightly
    - In-plane couples with torsion
  - Noticeable influence on gust loads
WP 3 - Reduced reliance on wind tunnel data (lead by DLR)

**Task T3.2** Investigation of modifications to the gust load process

**Subtask T3.2.1** Assessment of the impact of linear history effects on the aeroelastic model and gust

- Improvement of **AIC correction** method CREAM for small-scale gust encounter at separated flow conditions
- Implementation of **frequency-domain coupled gust analysis** simulation process based on TAU-LFD and CREAM GAFs to assess the effect of unsteady aero improvements in realistic gust scenarios (including rigid-body and elastic motion)
- Upcoming: D3.3 (31/01/2017)
Large-scale demonstration incl. fluid-structure coupling:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number</td>
<td>0.83</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>2.0165 deg</td>
</tr>
<tr>
<td>Velocity</td>
<td>246.124 m/s</td>
</tr>
<tr>
<td>Density</td>
<td>0.3796 kg/m^3</td>
</tr>
<tr>
<td>Vertical load factor</td>
<td>~1.0</td>
</tr>
<tr>
<td>Maximum y+</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Frequency-domain coupled gust analysis simulation process:

\[ S(s) = (K + s^2M)^{-1} \]

\[ G(s) = \frac{A(s)}{1 - A(s)S(s)} \]
Large-scale demonstration incl. fluid-structure coupling:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>198 450 kg</td>
</tr>
<tr>
<td>Inertia of Rotation</td>
<td>2.01E7 kg*m^2</td>
</tr>
<tr>
<td>Eigenfrequency 07</td>
<td>1.0003 Hz</td>
</tr>
</tbody>
</table>

3 structural DOFs!
Large-scale demonstration incl. fluid-structure coupling:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gust length</td>
<td>85.9 m</td>
</tr>
<tr>
<td>Gust velocity</td>
<td>246.12 m/s</td>
</tr>
<tr>
<td>Gust amplitude</td>
<td>0.43 m/s</td>
</tr>
<tr>
<td>Gust length / MAC</td>
<td>7.95</td>
</tr>
<tr>
<td>MAC</td>
<td>10.81 m</td>
</tr>
</tbody>
</table>

$max. \alpha_g=0.1°$
Large-scale demonstration incl. fluid-structure coupling:

**Fixed Aircraft!**
Aero only! No fluid-structure coupling yet!

Reference: Nonlinear TAU

```
GAF 03
GAF 05
GAF 07
```

**Parameters:**
- **N/m**
- **N/rad**
- **N/(m*kg)**

**Units:**
- Linear Force Density (LFD)
- Reference
Large-scale demonstration incl. fluid-structure coupling:

Fixed Aircraft! Aero only! No fluid-structure coupling yet!

Reference: Nonlinear TAU
Large-scale demonstration incl. fluid-structure coupling:

- GAF 03
- GAF 05
- GAF 07

Reference: Nonlinear FSI

Elastic Aircraft! Fluid-structure coupled solution!
Large-scale demonstration incl. fluid-structure coupling:

Reference: Nonlinear FSI
Large-scale demonstration incl. fluid-structure coupling:

- mode 03
- mode 05
- mode 07

Reference: Nonlinear FSI

Elastic Aircraft! Fluid-structure coupled solution!
Large-scale demonstration incl. fluid-structure coupling:

- mode 03
- mode 05
- mode 07

Reference: Nonlinear FSI

Elastic Aircraft! Fluid-structure coupled solution!
Next steps

- Replace TAU-LFD/uncorrected DLM with CREAM GAFs
- Apply to another config? CRM/Fermat?
- Towards D3.3: „Linear history effects“ = Quasi-steady AIC correction?
WP 4 - Adapting the loads process for non-linear and innovative structures (lead by UCT)

Task T4.1 New ROM developments for gusts (by INRIA, DLR, UNIVBRIS, Optimad and NUMECA)

Subtask T4.1.2
- Analytical linearization of RHS of Linear Frequency Domain (LFD) solver
  1) Extension of LFD to gusts (already done, see WP3)
  2) Global ROM of LFD solver for gusts
  3) Nonlinear unsteady least-squares (LSQ) ROM approach for gusts
  4) Gust simulations with TAU full-order model (reference)
- Comparison of the four methods
M12 - outcomes

- Nonlinear LSQ ROM predictions
  - with MPE
  - LANN wing 3D test case
  - pitching oscillation forced motion

- Offline accelerated greedy missing point estimation (MPE) procedure still slow

M18 - outcomes

- Nonlinear LSQ ROM predictions
  - w/o MPE
  - XRF-1 full aircraft
  - pitching oscillation forced motion

- Improvement (parallelization and algorithm) of the accelerated greedy MPE procedure

Online speed-up of 26.7 over the full-order model

Online speed-up of 2.3 over the full-order model
T4.1.2 - Nonlinear unsteady LSQ-ROM approach

Search for an approximated solution $w = [\rho, \rho v, \rho E^t, \nu_t] \in \mathbb{R}^N$

- in the POD subspace $U_r \in \mathbb{R}^{N \times r}, r \ll N$
- minimizing a subset of the unsteady residual in the $L_2$ norm
- greedy missing point estimation (MPE) procedure to select the subset

$$w \approx \sum_{i=1}^{r} a_i U^i + \bar{w} = U_r a + \bar{w}$$

$a$: vector of the unknown coefficients $a_i$

$\bar{w}$: mean of the snapshots set

Nonlinear least squares problem

$$\min_a \| \hat{R}^* (U_r a + \bar{w}) \|_{L_2}$$

- $N$: order of CFD model (variables x nodes)
- $r$: order of the ROM (i.e. number of POD modes)
Building the POD subspace

Collecting snapshots coming from an unsteady simulation → variation in the local effective angle of attack

- Boundary conditions disturbances
- Motion (forced or induced)
- Gust perturbations → frozen formulation, rigid aircraft, no motion

OFFLINE

Training input

\[ \text{Angle of Attack / Gust intensity } v_g \]

\[ \text{time} \]

Training output

\[ C_L \]

\[ w(t_i \ldots t_j) \]

Flow field output time history

\[ \text{Global POD + MPE} \]

ONLINE

ROM prediction

\[ (L_g, A_g)_X \]

Flow field output time history!
ROM prediction assessment for a full aircraft

Forced Motion

Training maneuver
Chirp pitching oscillation up to reduced frequency $k=3$

Training @ Mach = 0.83, Re = 6.5*1e6

Predicted maneuver
(1-cos)–like pitching oscillation

Predicted maneuver

$V_\infty = 246 \text{ m/s}$

$w_g = 10 \text{ m/s}$

$\Delta \alpha \approx 2.3^\circ$

$\dot{\alpha} \approx \omega_g$

$V_\infty = 246 \text{ m/s}$

Forced Motion

Training maneuver
Chirp pitching oscillation up to reduced frequency $k=3$

ROM run-time (48 cores): 1.3 h
Speed-up: 2.3
Improvement of the accelerated greedy MPE procedure

Using an (additional) **rank-1 SVD update** within the iterative greedy step, to further accelerate the selection of the grid nodes.

**Computational cost**
- Alg. Ref. [1]: $\mathcal{O}(Nr^2s + r^3s)$
- Rank-1 SVD update: $\mathcal{O}(Nr^2s + r^3s)$

- $N$: order of CFD model (variables x nodes)
- $r$: order of the ROM (i.e. number of POD modes)
- $s (> r)$: number of MPE selected nodes

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Improvement of the accelerated greedy MPE procedure

Grid
N° nodes: 3.8 Mi

Greedy MPE
N° nodes: 0.19 Mi (5% of total nodes)

- 100 POD modes
- 48 processors
Improvement of the accelerated greedy MPE procedure

Grid
N° nodes: 3.8 Mi

Greedy MPE
N° nodes: 0.19 Mi
(5% of total nodes)

- 100 POD modes
- 48 processors
Next steps

- Include the greedy MPE selection in the ROM prediction for the full aircraft
- Apply the nonlinear unsteady least-squares ROM approach to discrete gusts
- D4.2 – “Report on comparison of gust ROMs with gusts computed with Linear Frequency Domain solver and TAU” (M15 → M30)