Numeca

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

Presented by B. Tartinville
Objectives:

To carry investigations using CFD so that the non-linearities in gust interactions are understood.

To create a gust loads process that does not require wind tunnel data and hence reduces the need for wind tunnel testing.

To develop updated reduced order models for gust prediction that account for non-linearity at an acceptable cost.

5 WPs and Numeca involved in all of them (except WP1: management) and Numflio as a third party.
WP2: T2.2  Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- Survey of high fidelity LES/DES methods for gust simulations.  
- Application to airfoil geometry.  
- Application of hybrid methods to investigate future full aircraft gust simulation.

Period: M1-M30

Deliverables @ M6, M18 and M30
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- Application to airfoil geometry.
- Final test case description has been defined: FFAST crank airfoil with flow condition “I”
  - Altitude: 35,000 ft
  - Free stream Mach number = 0.86 ($U_\infty = 255$ m/s)
  - Chord length: 8 m
  - Three gust scenario
- The span-wise extend has been set to half chord (based on best practices for LES/DES).
- A low dissipation scheme has been retained: 2nd order Jameson FV scheme with Matrix dissipation.
- A structured 3D mesh with $16 \times 10^6$ cells has been generated (65 points span-wise) and mesh convergence has been verified: difference in drag between the two finest grids is less than one count.
WP2: T2.2  Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- Distribution of mesh points in the far field is sufficiently small to be able to capture the gust length.
- Computational domain extend 20 chords upstream and downstream with a O mesh topology -> domain size 320 m
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil without gust.
- 90 chord convective time steps (3 s) have been computed and a “pseudo periodic” state has been reached.

Animations over the last 0.5 s
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil without gust.
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil with gust (H=30 ft).
- Gust is imposed via a time evolution of vertical velocity along the far-field boundaries.

Example of time-evolution of vertical velocity along the far-field boundaries @ x/C=-20
WP2: T2.2  Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil with gust (H=30ft).
- Simulation starts from the one without gust.

Max Lift coeff = 0.260  @ t = 0.694 sec
Min Lift coeff = 0.110  @ t = 0.769 sec
WP2: T2.2  Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil with gust (H=30ft).

Mid-span Vertical velocity distribution [m/s]
Mid-span static pressure distribution [Pa]
WP2: T2.2  Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil with gust (H=30ft).

Mid-span Mach number distribution

Velocity magnitude distribution [m/s] on iso-surface of $\lambda_2=-5000$
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- IDDES simulation of the FFAST crank airfoil with gust (H=30ft).
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- Application of hybrid methods to investigate future full aircraft gust simulation.
- A Navier-Stokes high order solver on unstructured grid is under development at Numeca.
- Validated up to 4th order accuracy (laminar flow)
- Explicit time integration

Viscous subsonic flow around NACA0012.

Contours of Mach number, on coarse mesh of 2,240 hexas, with p=1, p=2, and p=3. Reference solution with FINE/Open (right), on a very fine mesh of 143,360 hexas (mesh independent solution), with 2nd order Jameson FV scheme with Matrix dissipation.
WP2: T2.2 Non-linear Aerodynamics of Gust Using LES/DES (9MM)

- Application of hybrid methods to investigate future full aircraft gust simulation.
- Ongoing developments focus on:
  - improving the solver efficiency and parallel scalability in order to perform unsteady turbulence-resolving simulations.
  - In house generation of high-order meshes.

Contours of Density for the isentropic vortex with $p=2$, $p=3$, and $p=4$ (from left to right) (mesh $32\times32$).
WP3: T3.3  Introduction of uncertainties into the gust load process (6MM)

- Development of methods to determine the effects of aerodynamic and structural uncertainties on the worst case loads.

**Period:** M21-M30

**Deliverable @ M30**
WP4: T4.1 New ROM development for gusts
T4.5 Investigation of aeroelastic ROM for gusts (20MM total) Ongoing

- Fourier decomposition ROM for gusts

Period: M9-M33

Deliverables @ M24, and M33
WP4: T4.1  New ROM development for gusts

- Application to FFAST crank airfoil geometry

Gust definitions

\[ U = A_s F_g \frac{U_g}{2} \left[ 1 - \cos \left( \frac{\pi l}{H} \right) \right], \]

for \( 0 \leq l \leq 2H \),

\[ U_g = U_{ref} \left( \frac{H}{350} \right)^{1/6}, \]

<table>
<thead>
<tr>
<th>Case</th>
<th>( U_g ) (ft/s)</th>
<th>( l_g ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H=30ft</td>
<td>37.18</td>
<td>125</td>
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<tr>
<td>H=150ft</td>
<td>48.62</td>
<td>500</td>
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<tr>
<td>H=300ft</td>
<td>56.00</td>
<td>875</td>
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</tbody>
</table>
WP4: T4.1 New ROM development for gusts

- Application to FFAST crank airfoil geometry
- Gust is made periodic by time windowing.
- Gust is defined in the frequency domain by a discrete Fourier transform.

![Gust windowing](image)

**Gust along profile**

![Gust 30ft spectrum](image)

**Gust 30ft spectrum**

- Time window = 10 x gust length
- DFT
- Initial
- Repetition
WP4: T4.1 New ROM development for gusts

- The number of harmonics retains influences the frequency range covered by the computation and the accuracy with which the gust is described.
WP4: T4.1  New ROM development for gusts

- The gust windowing influences both the amplitude and the number of harmonics in the gust spectrum.

![Gust windowing](image1.png)

![Gust 30ft spectrum](image2.png)
WP4: T4.1 New ROM development for gusts

Open questions to be investigated

- What is the best number of harmonics giving an accurate gust model at the lowest cost?
- What is the best time window for gust repetition giving an accurate gust model at the lowest cost?

Tests on rigid crank airfoil

- Cylindrical domain centred at leading edge (R = 20 chords, H = 0.5 chord)
- 0.7 million mesh nodes (77 602 x 9 span layers)

- Stability issue encountered for configuration I at M=0.86 → use configuration D at M=0.754
WP4: T4.1 New ROM development for gusts

- Comparison of flow solutions without gust for configuration I (M=0.86) and configuration D (M=0.754)
  - Stronger shock for configuration I
  - Shock induced detachment for configuration I
WP4: T4.1  New ROM development for gusts

- Influence of spectrum truncation for 30 ft gust height
  → Truncated spectrum can be restricted to first “bump”
  → Switching from 20 harmonics to 40 harmonics increases the CPU cost by a factor 3.6 and memory by a factor 1.94

Contribution from Numeca (WP4)
WP4: T4.1 New ROM development for gusts

- Influence of gust windowing at constant frequency range for 30 ft gust height
  - Trends properly modeled with a 10 gust lengths period
  - Discrepancies mainly observed for out-of-gust solutions
  - Reduction of repetition period allows a reduction of the number of harmonics to solve for the same frequency range

Gust H=30ft - Time evolution of lift

Gust H=30ft - Time evolution of moment
WP4: T4.1 New ROM development for gusts

- Influence of spectrum truncation for 150ft gust height
  - With 20 harmonics fluctuations of $Cm$ are still visible after gust passage
  - Consideration of 40 harmonics removes these fluctuations
  - Strange decrease of $Cl$ and $Cm$ just before half-simulation period to be investigated
WP4: T4.1  New ROM development for gusts

- Influence of gust windowing at constant frequency range for 150ft gust height
  - Same trends for both gust repetition periods
  - Observed decrease of $C_l$ and $C_m$ just before 2s not related to gust repetition period

![Graphs showing time evolution of lift and moment for 10 and 20 gust lengths]
WP4:T4.5 Investigation of aeroelastic ROM for gusts

• The NLH method

The instantaneous conservative flow variables \( U = (\rho, \rho v_x, \rho v_y, \rho v_x, \rho E) \) are decomposed into a time-averaged value \( \bar{U} \) and a sum of unsteady perturbations \( U''_n \), assumed to be periodic:

\[
U (\bar{x}, t) = \bar{U} (\bar{x}) + \sum_n U''_n (\bar{x}, t)
\]

A Fourier decomposition is applied to each of the periodic perturbations. Hence, every perturbation \( U''_n \) can be written as a finite sum of \( N_h \) time harmonics:

\[
U''_n (\bar{x}, t) = \sum_{h=1}^{N_h} \left[ \bar{U}|_h (\bar{x}) e^{I \omega_h t} + \bar{U}|-h (\bar{x}) e^{-I \omega_h t} \right] = 2 \sum_{h=1}^{N_h} \left[ \bar{U}_{hRe} \cos (\omega_h t) - \bar{U}_{hIm} \sin (\omega_h t) \right]
\]

where the harmonic amplitudes \( \bar{U}|_h \) and \( \bar{U}|-h \) are complex conjugates related to the \( n^{th} \) perturbation and defined by the real part \( \bar{U}_{hRe} \) and the imaginary part \( \bar{U}_{hIm} \).

The value of \( N_h \) is an input of the method, driving both the frequency and space resolution of the computed flow unsteadiness.

For the particular case of rotating machinery applications, the fundamental harmonic frequency \( \omega_1 \) can be related to the Blade Passing Frequency (BPF).
WP4:T4.5  Investigation of aeroelastic ROM for gusts

The NLH formulation is derived by introducing this variable decomposition into the unsteady Navier-Stokes equations. A new set of equations is obtained, associated to the time-mean contribution of every conservation law and the corresponding harmonics. In finite-volume compact formulation:

\[
\frac{\partial \tilde{U}}{\partial \tau} + \sum_{\text{cell faces}} \left( \tilde{F}_C - \tilde{F}_V \right) \cdot \tilde{S} = Q \Omega
\]

Obtained equations are only space-dependent, their resolution is performed through the pseudo-time derivative. This justifies the computational time saving of the NLH method. Together with the mesh of a single blade passage. The harmonic solution can be reconstructed in time to perform a more comprehensive post-processing of the unsteady flow.
WP4:T4.5 Investigation of aeroelastic ROM for gusts

- Structure modeling: modal approach
  Aeroelastic equilibrium based on linear dynamics equation:

\[
\mathbf{M} \frac{\partial^2 \mathbf{u}}{\partial t^2} + \mathbf{C} \frac{\partial \mathbf{u}}{\partial t} + \mathbf{K} \mathbf{u} = \mathbf{f}_S
\]

A modal basis of the structure can be obtained by solving the eigen value problem when assuming no loading and no damping:

\[
\mathbf{M} \frac{\partial^2 \mathbf{\hat{u}}}{\partial t^2} + \mathbf{K} \mathbf{\hat{u}} = \mathbf{0}
\]

\[
\omega_k = \sqrt{\lambda_k} \quad \text{Natural frequencies (related to eigen values)}
\]

\[
\phi_k \quad \text{Mode shapes (i.e. eigen vectors)}
\]

The linear dynamics equation can be expressed based on this basis. Normalizing the mode shapes by the mass, assuming Rayleigh damping \( \mathbf{C} = \alpha \mathbf{M} + \beta \mathbf{K} \), and a frequency-independent stiffness, it can be uncoupled for every mode \( k \) as:

\[
\frac{\partial^2 q_k}{\partial t^2} + 2\xi_k \omega_k \frac{\partial q_k}{\partial t} + \omega_k^2 q_k = \phi_k^T \mathbf{f}_S
\]

With the generalized displacements \( q_k \) that can be related to the deformations as:

\[
\mathbf{u} = \sum_{k=1}^{N_k} q_k \phi_k
\]
WP4:T4.5  Investigation of aeroelastic ROM for gusts

In order to obtain a formulation adapted to the NLH solver, variables are decomposed into time-averaged and harmonic contributions:

\[ q_k (\bar{x}, t) = \bar{q}_k (\bar{x}) + \sum_n q''_{k,n} (\bar{x}, t) \]

\[ \tilde{f}_S (\bar{x}, t) = \tilde{f}_S (\bar{x}) + \sum_n \tilde{f}''_{S,n} (\bar{x}, t) \]

Introducing this decomposition into the linear dynamics equations and simplifying the set of perturbations by \( q''_k \) and \( \tilde{f}''_S \):

\[
\frac{\partial^2 (q_k + q''_k)}{\partial t^2} + 2\xi_k \omega_k \frac{\partial (q_k + q''_k)}{\partial t} + \omega_k^2 (q_k + q''_k) = \phi_k^T \left( \tilde{f}_S + \tilde{f}''_S \right)
\]

**Time-mean equation**

\[ \bar{q}_k = \frac{\bar{\phi}_k^T \bar{f}_S}{\omega_k^2} \]

\[ \bar{\tilde{u}} = \sum_{k=1}^{N_t} \bar{q}_k \bar{\phi}_k \]

**Harmonic equation**

\[ \tilde{q}_k |_h = \frac{\bar{\phi}_k^T \bar{f}_S |_h}{\omega_k^2 - \omega_h^2 + 2\iota \xi_k \omega_k \omega_h} \]

\[ \tilde{u} |_h = \sum_{k=1}^{N_t} \tilde{q}_k |_h \bar{\phi}_k \]
WP4:T4.5 Investigation of aeroelastic ROM for gusts

- Application to FFAST crank airfoil geometry
- Structural model given in D5.2 for unit mode shapes

\[
M = \begin{bmatrix}
824.8 & -1944 \\
-1944 & 10602
\end{bmatrix}
\quad \text{and} \quad
K = \begin{bmatrix}
1.36 \times 10^5 & 0 \\
0 & 1.80 \times 10^5
\end{bmatrix}
\]

with \( \phi_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \) and \( \phi_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \)

Mass-normalization

\[
M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\quad \text{and} \quad
K = \begin{bmatrix}
100.93 & 0 \\
0 & 448.45
\end{bmatrix}
\]

with \( \phi_1 = \begin{bmatrix} -0.01947643 \\ 0.00523586 \end{bmatrix} \) and \( \phi_2 = \begin{bmatrix} -0.04190283 \\ -0.0117769 \end{bmatrix} \)

Static displacement induced by free stream flow (configuration I) without gust:
- Heave : -0.115 m
- Pitch : 0.136°

Unsteady displacement induced by gust are ongoing.
WP5: T5.3  Comparison and analysis

- Comparison and evaluation of results.

**Period:** M9-M33

**Deliverable** @ M12 and M24

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>Gust condition (Fg=1.0)</th>
<th>UNIBRIS</th>
<th>INRIA</th>
<th>NLR</th>
<th>DLR</th>
<th>UCT</th>
<th>NUMECA</th>
<th>OPTIMAD</th>
<th>LLIV</th>
<th>AIRBUS</th>
<th>DASSAV</th>
<th>PIAGGIO</th>
<th>VALEOL</th>
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<tbody>
<tr>
<td>FFS 660 crank airfoil</td>
<td>H=30 ft</td>
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<td>H=150 ft</td>
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<td>H=350 ft</td>
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| NASA LRN 1015 airfoil | H=30 ft | | | | | | | | | | | |
|                       | H=150 ft | | | | | | | | | | | |
|                       | H=350 ft | | | | | | | | | | | |

| AGARD 445.6 wing | H=30 ft | | | | | | | | | | | |
|                  | H=150 ft | | | | | | | | | | | |
|                  | H=350 ft | | | | | | | | | | | |

| NASA CRM | H=30 ft | | | | | | | | | | | |
|          | H=150 ft | | | | | | | | | | | |
|          | H=350 ft | | | | | | | | | | | |

<table>
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<tr>
<th>Wind turbine</th>
<th>Gust condition (class IIB)</th>
<th>UNIBRIS</th>
<th>INRIA</th>
<th>NLR</th>
<th>DLR</th>
<th>UCT</th>
<th>NUMECA</th>
<th>OPTIMAD</th>
<th>LLIV</th>
<th>AIRBUS</th>
<th>DASSAV</th>
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<tr>
<td></td>
<td>Vhub = 25m/s</td>
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Contribution from Numeca (WP5)
### Contribution from Numeca

<table>
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<tr>
<th>WP</th>
<th>Task</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
<td>2</td>
<td>2.2.1</td>
<td>D-2.1</td>
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Start date 1st May 2015.

- D-2.1: Done
- D-2.9: Ongoing
- D-2.13: Ongoing
- D-3.8: Ongoing
- D-4.5: Ongoing
- D-4.16: Ongoing
- D-5.7: Ongoing
- D-5.8: Ongoing