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Exascale performance evaluation of a sustainable aircraft prototype

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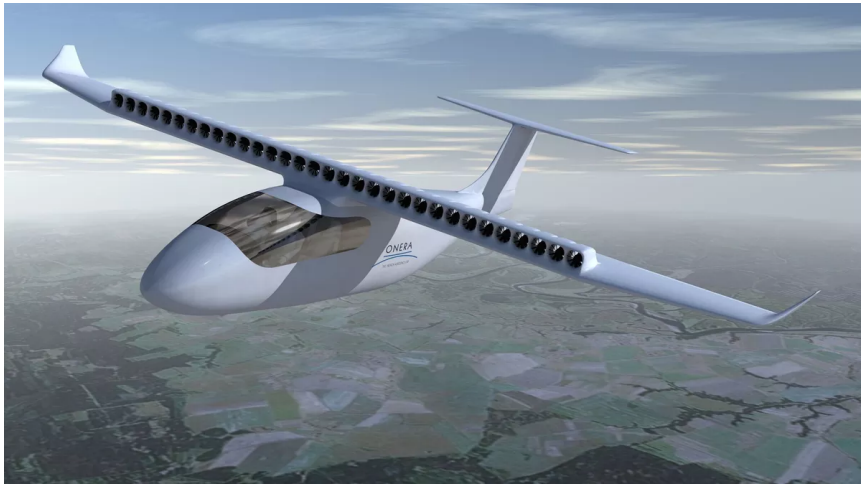
Efficient discretization for PDE@Exascale
CEA, November 7-8, 2023

ONERA @NumPEx/ExaDIP

- **Dec 22, 2022**: ONERA's application demonstrator (AD) proposal;
- **Feb 24, 2023**: NumPEx launching; including ONERA's AD "Simuler pour concevoir les avions décarbonés du futur."
- **Apr 05, 2023**: acceptance of ONERA's AD;
- **Ongoing**: definition of the AD configuration.

Exascale simulation for sustainable aircraft

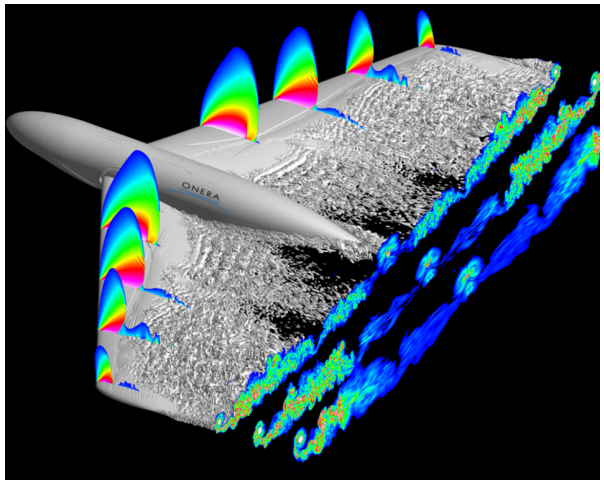
Small-Medium range Integrated Light and Efficient (SMILE) blended wing body configuration

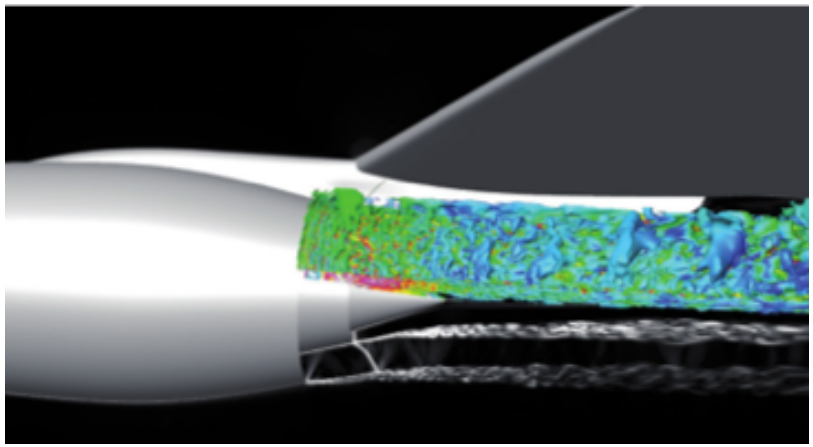


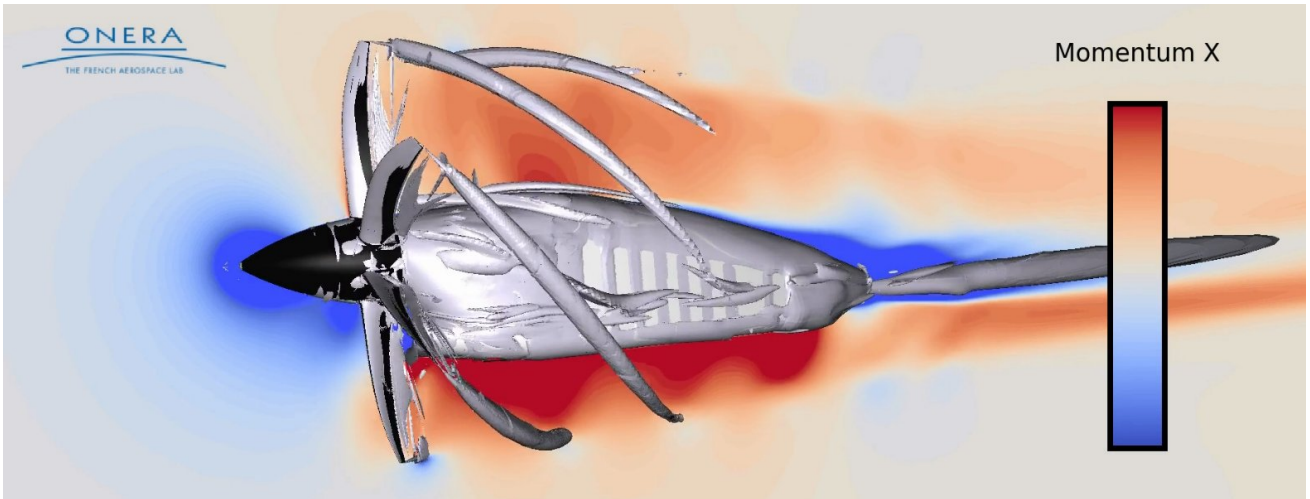
Avion à Motorisation réPartie Électrique de Recherche Expérimentale (AMPERE) distributed electric propulsion configuration

- Novel carbon-neutral fuel sources for aircraft, *e.g.* hydrogen fuel cells;
- Redesign of aircraft, *e.g.* distributed electric propulsion;
- Reduce expensive, time consuming and environmentally damaging physical testing;
- Toward certification by simulation.

Exascale simulation for sustainable aircraft







Full aero-structural simulation at exascale

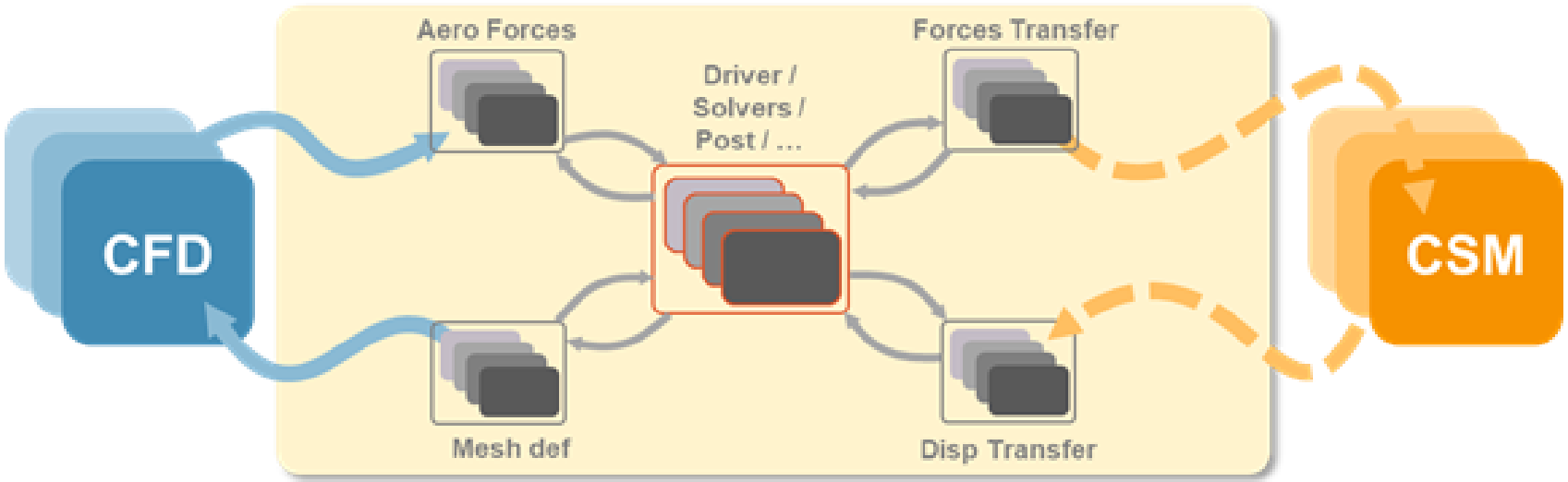
Objectives: high-fidelity simulation of transient turbulent flow about an aircraft including its structural response.

- **O1**: Exascale capacity of all software modules (G1);
- **O2**: Adaptive mesh refinement and movement (algorithmic motif AM1);
- **O3**: Efficient code coupling *via* non conforming interfaces (algorithmic motif AM2).

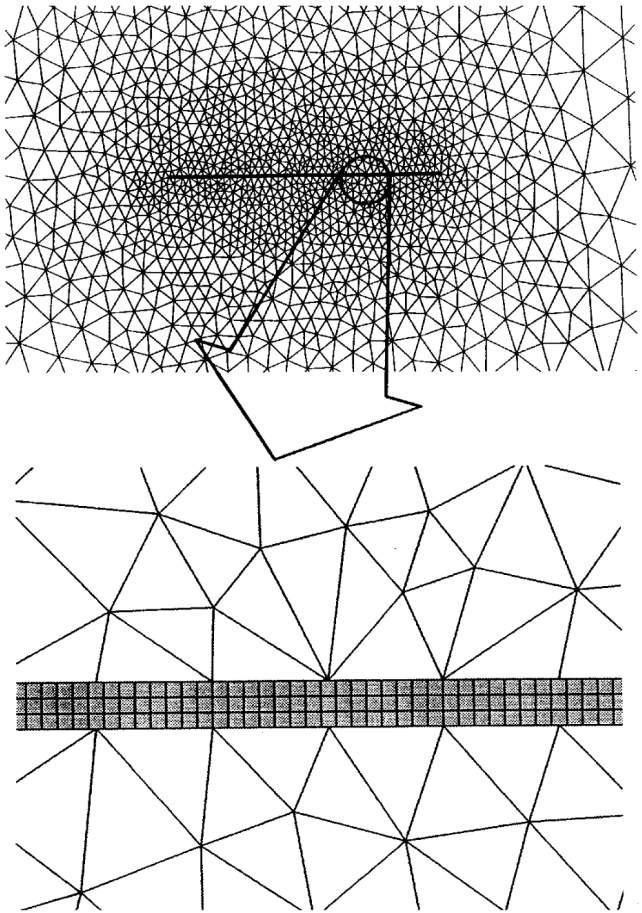
In-house softwares:

- `SoNICS`: computational fluid dynamics (CFD);
- `A-Set`/`CutFEMx`: computational structural mechanics (CSM);
- `ParaDiGM`/`CWIPI`: meshing and coupling.

Full aero-structural simulation at exascale



Full aero-structural simulation at exascale



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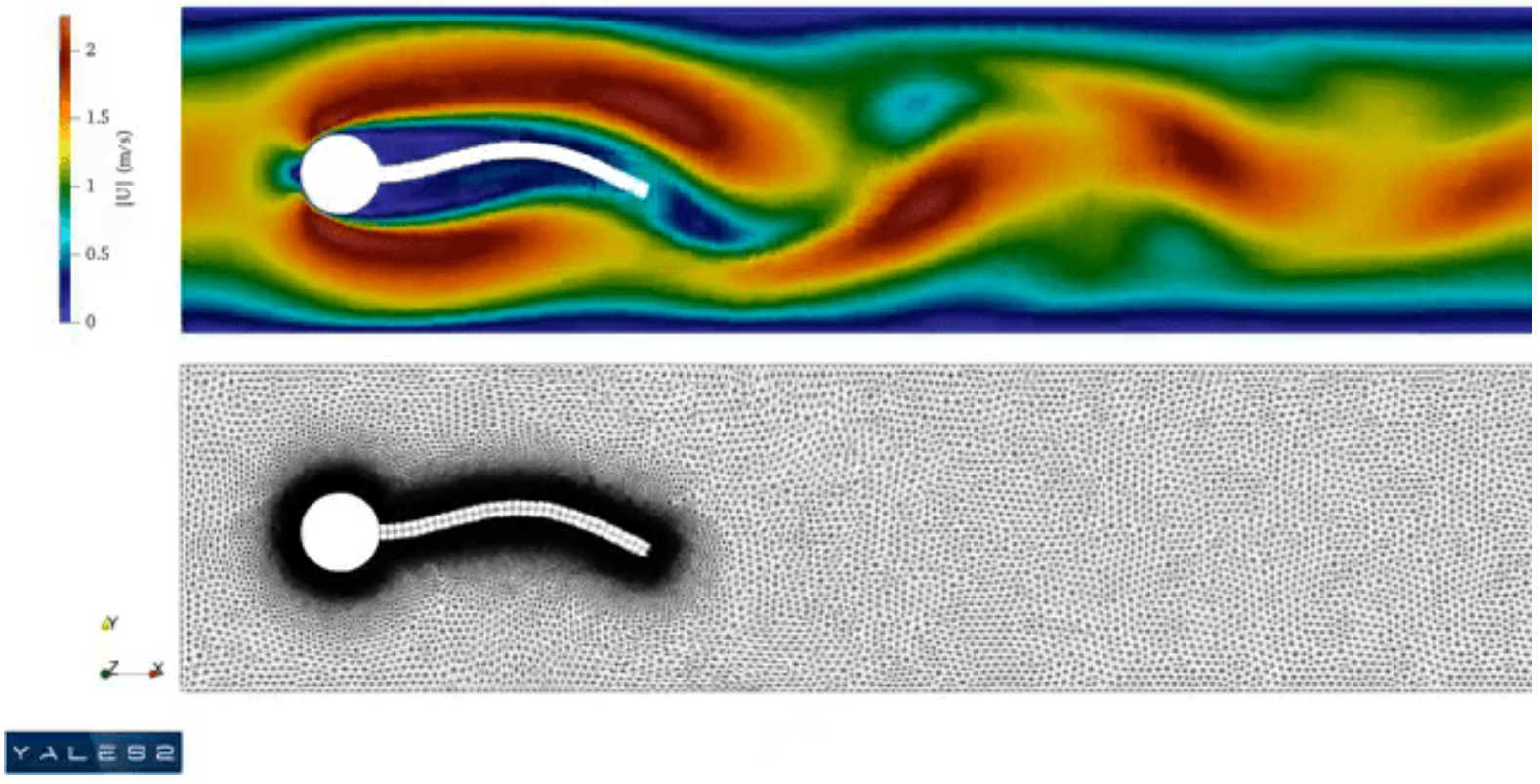
Full aero-structural simulation at exascale



https://youtu.be/qLWOg_EJtTM

O1—Improvement of existing codes up to exascale

Performance analysis

- SoNICS, A-Set/CutFEMx, ParaDiGM, MAIA: pre-exascale and exascale performance tests and improvement.

CPU/GPU hybrid algorithms

- ParaDiGM: *k*–Nearest Neighbors, wall distance, intersections, iso-surfaces with CPU/GPUs.

PC1-WP3, PC2-WP3, PC2-WP4, PC2-WP5, PC3-WP1

PhD proposal @ExaMA with IFPEN: Neural linear solvers and preconditioners for general sparse matrices [PC1-WP2, PC1-WP3, B6, B8, B9].

O2—Adaptive mesh

Parallel algorithms for adaptive mesh refinement (AMR)

- Extending existing algorithm up to exascale (in cooperation with GammaO at Inria).

Distributed/parallel algorithms have to see the whole mesh locally

- Existing algorithms based on the Fast Multipole Method or Radial Basis Functions copy the whole mesh for each node.
- This is not adapted to exascale platforms $\Rightarrow$ need of fully parallel algorithms.

PC1-WP1

O2—Mesh movement

Finite volume cells movement

- Existing algorithm: not fully parallel and not optimized.
- Use of a finite element software (*e.g.* `A-Set`) for parallel mesh movement.

Surface mesh distribution and source points

- Memory optimization and computational complexity improvement of mesh movement algorithms such as TransFinite Interpolation (TFI), Inverse Distance Weighting (IDW) interpolation method, or Quantum.
- Reducing the number of source points using k–d Trees or k–Nearest Neighbors.
- In existing algorithms all source points are dispatched over all processors. In future algorithms they shall be spread on several processors, and the surface mesh should not be multiply copied.

O3—Aero-elastic coupling

Interfacing CSM solvers using ParaDiGM

- A-Set/CutFEMx and ParaDiGM/CWIPI APIs in order to:

1. share meshes and inputs/outputs;
2. implement standard coupling conditions.

Sequential coupling of CFD and CSM solvers

- Sequential coupling of SoNICS/A-Set/CutFEMx *via* the aforementioned APIs and using mesh movement.

Parallelization of the coupling

- Parallel coupling of SoNICS/A-Set/CutFEMx;
- Data memory access;
- Parallel pre/post.

O3—Aero-elastic coupling

Coupling through non-conforming interfaces

- CSM meshes are coarser than CFD meshes.
- Different AMR needs: *e.g.* eddies vs. stress concentration.
- Twofold strategy to couple "fluid" and "structure" meshes:

1. Immersed Boundary Method for the fluid surface which is embedded in a coarse structural mesh by `CutFEMx`. `CutFEMx`/`ParaDiGM` interfacing needs to be extended in this approach;
2. Non conformal interface coupling in aeroelastic computation for the transfer of loads and displacements through point clouds:
   - Nearest Neighbors/Virtual Work approaches for load transfers,
   - Volume Spline approach for displacement transfers.

   These approaches shall be adapted to HPC at exascale using k–Nearest Neighbors and Radial Basis Function algorithms.

PC1-WP1, PC2-WP1, PC2-WP4, PC3-WP1, PC3-WP2

Validation cases

C1—Large Reference model-High Lift (LRM-HL) experimental data at ONERA/F1

- Wind tunnel dataset for the High Lift Prediction Workshop (HLPW5), June 2024, `https://hiliftpw.larc.nasa.gov/`;
- Validation of `SoNICS` with mesh adaption.

C2—Aeroelastic gust load prediction at ONERA/S3Ch

- Flexible wIng Gust REsponse ONERA/DLR project (2018-2021) on CARACAL (Conception aéroélastique pour la réduction de charge à la rafale) configuration;
- Unsteady coupled structural (mesures déformée maquette, MDM) and pressure (pressure-sensitive paint, PSP) measurements;
- Validation of `SoNICS`/`A-Set` for conformal interface and `SoNICS`/`CutFEMx` for non-conformal interface.