Politecnico di Milano
Department of Aerospace Science and Technology

COUPLED MULTIBODY–MID FIDELITY AERODYNAMIC SOLVER FOR TILTROTOR AEROELASTIC SIMULATION

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Tiltrotor are quite challenging machine to design since they must be able to combine both helicopter and fixed wing aircraft characteristics. Several difficulties arise in the design phase:

- Very different flight conditions: Hover, Conversion, Cruise.

Image taken from https://cnn.it/3xgPLvp

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- Rotor–Wing interaction must be taken into account also when flight mechanics maneuvers are considered.

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Coupling Multibody–Mid Fidelity Aerodynamic (VPM)

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Multibody

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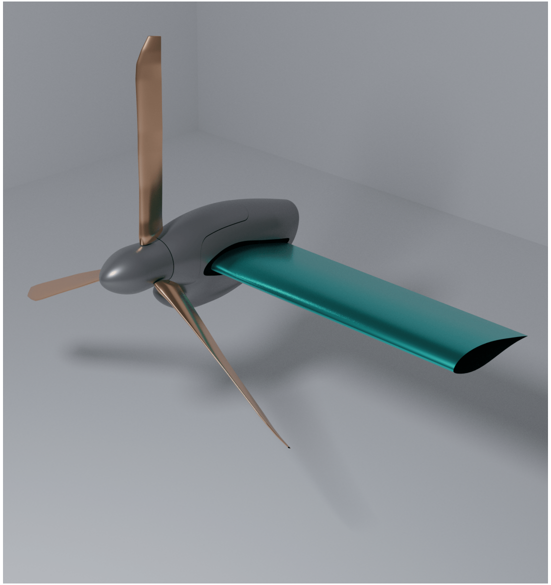
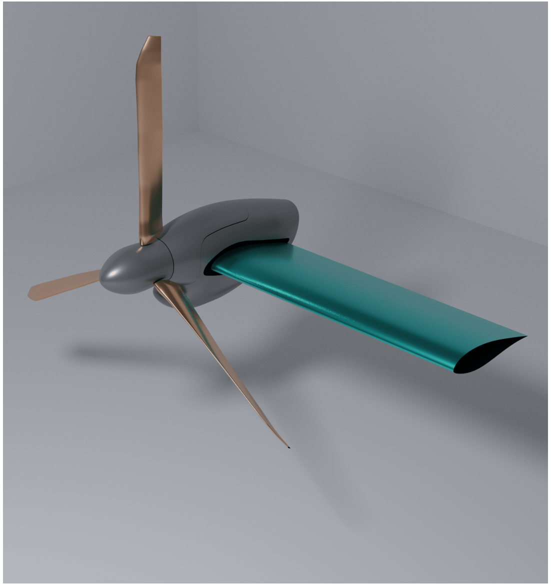
Mid fidelity Aerodynamic (VPM)

- Ease to assemble complex aircraft models
- Simulation of the entire aircraft with reasonable computational resources
- Interaction between the aerodynamic component is well captured



- MBDyn[a] features the integrated multidisciplinary simulation of multibody, multi–physics systems.



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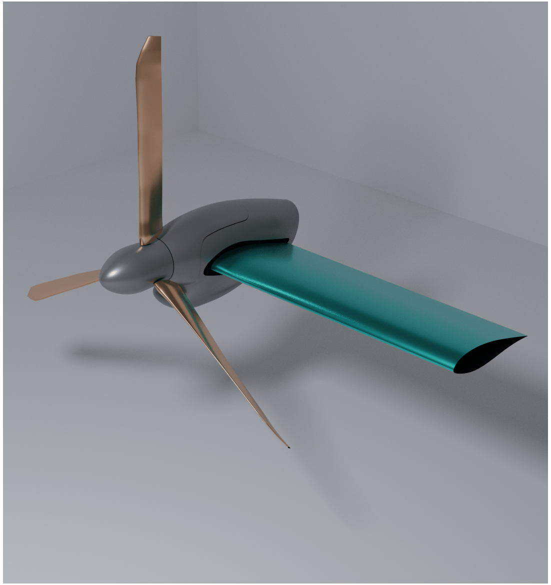
- Large amount of elements are available:
  - Nonlinear mechanics of rigid and flexible bodies (geometrically exact & composite-ready beam and shell finite elements)
  - Component mode synthesis elements (CMS)
  - Electric and hydraulic networks
  - Active control



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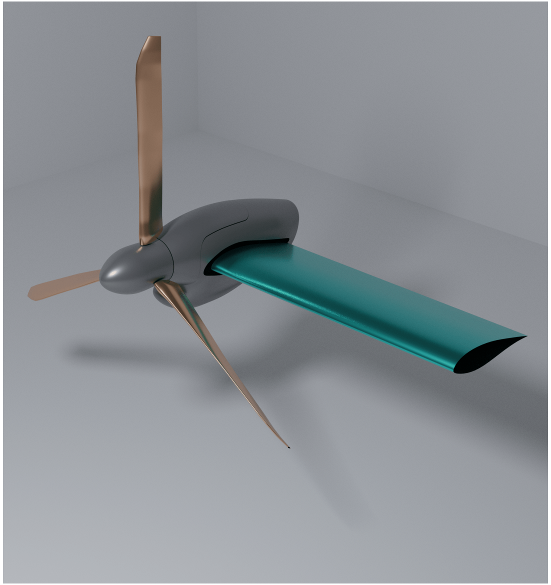

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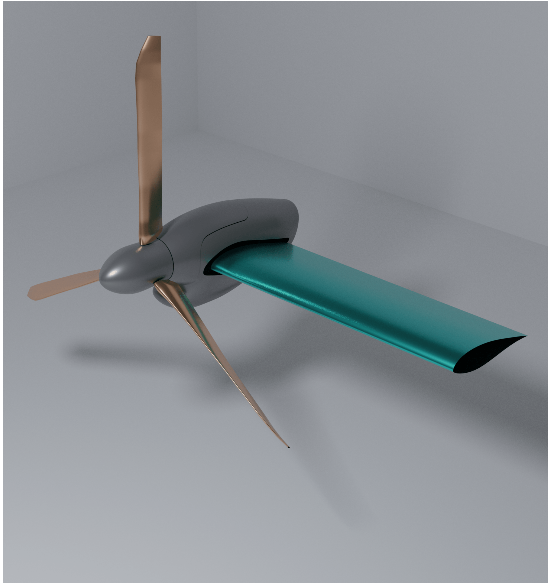
- The formulation consists in writing Newton–Euler equations of motion:

$$
\begin{aligned}
\mathbf{M}(\mathbf{x}, \mathbf{t})\dot{\mathbf{x}} &= \mathbf{p} \\
\dot{\mathbf{p}} &= \phi^T_{/\mathbf{x}}\boldsymbol{\lambda} + \mathbf{f}_i(\dot{\mathbf{x}}, \mathbf{x}, t) + \mathbf{f}_e(\dot{\mathbf{x}}, \mathbf{x}, t) \\
\phi(\mathbf{x}) &= \mathbf{0}
\end{aligned}
$$



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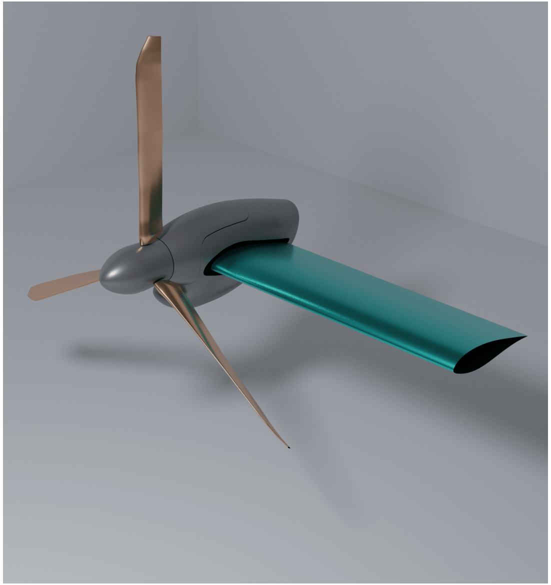
- MBDyn can be easily coupled to external solvers for co-simulation of multi–physics problems.



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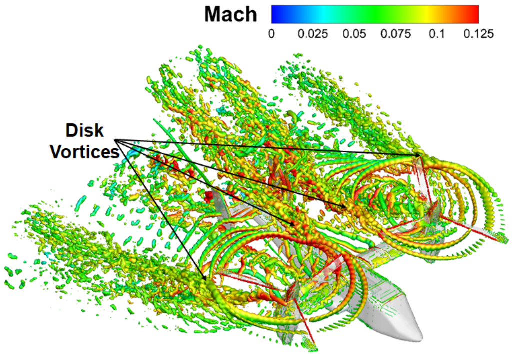
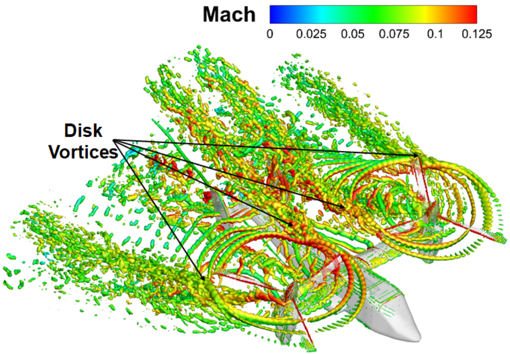
- MBDyn can be easily coupled to external solvers for co-simulation of multi–physics problems.
- MBDyn is being actively developed and used in the aerospace, wind energy, automotive, mechatronic, biomechanical fields.

[a] https://www.mbdyn.org/



- DUST [a] is a novel flexible solution to solve aerodynamics problems.



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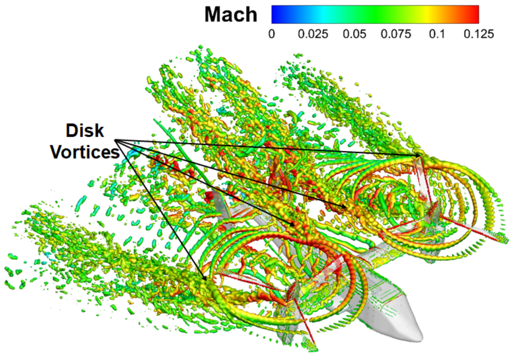

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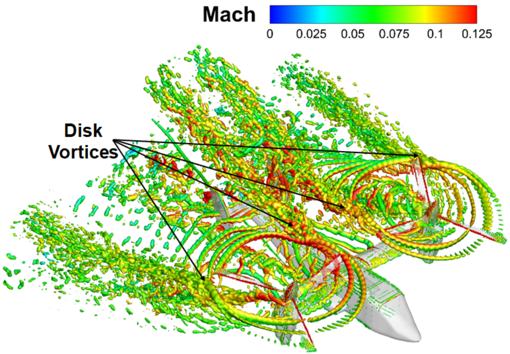
- Core features:
  - Flexible Geometry and Movement
  - Import custom surface meshes or build them parametrically
  - Multi fidelity levels models/elements: from 1D lifting line to 3D objects.



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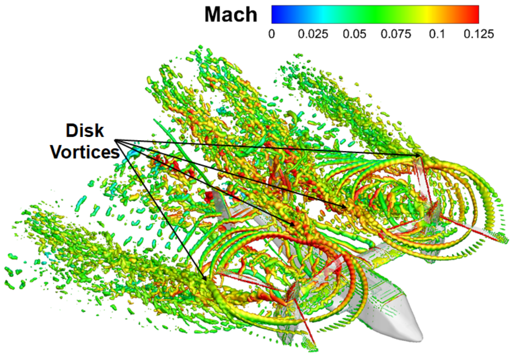

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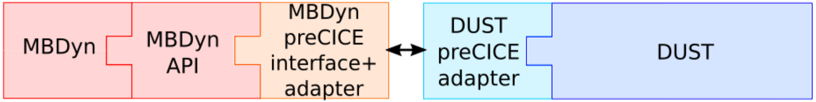
- The rotational velocity $\mathbf{u}_\psi$ allows to describe the wake evolution by a Lagrangian grid–free approach $\rightarrow$ no volume mesh needed

$$\boldsymbol{\omega}^h(\mathbf{r}, t) = \sum_{p=1}^{N_p} \boldsymbol{\alpha}_p(t)\zeta\left(\mathbf{r} - \mathbf{r}_p(t); R_p\right)$$

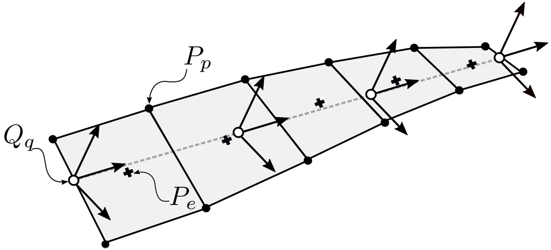
[a] https://www.dust-project.org/

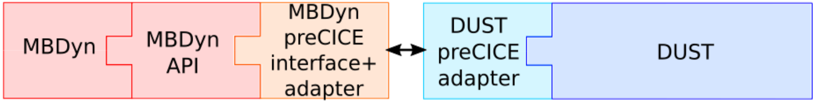


- Radial Basis Function (RBF) Interpolation

$$\phi_p = \sum_q w_{pq}\, \phi_q$$

$$\|(P_p - Q_q)\|^2 := \boldsymbol{r}_{pq}^T\, \mathbf{W}\, \boldsymbol{r}_{pq}$$





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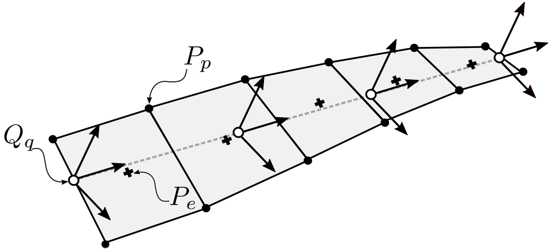
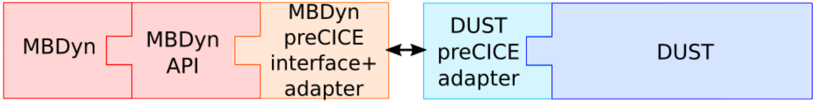
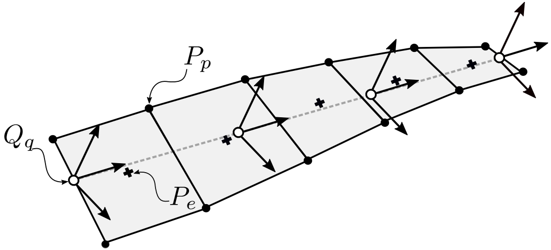


- Kinematic variables

$$(P_p - O)^g = \sum_{Q\in I_P} w_{pq}\left\{(Q_q - O)^g + \mathbf{R}_Q^{r\to g}(P_p - Q_q)\right\}$$





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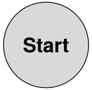
- Forces and moments

$$\boldsymbol{f}_Q = \sum_{e \in J_Q} w_{eq}\, \boldsymbol{f}_e$$

$$\boldsymbol{m}_Q = \sum_{e \in J_Q} w_{eq} \left\{ \boldsymbol{m}_e + (P_e - Q_q) \times \boldsymbol{f}_e \right\}$$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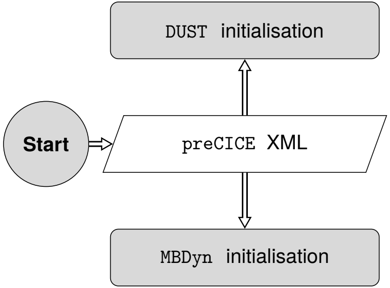
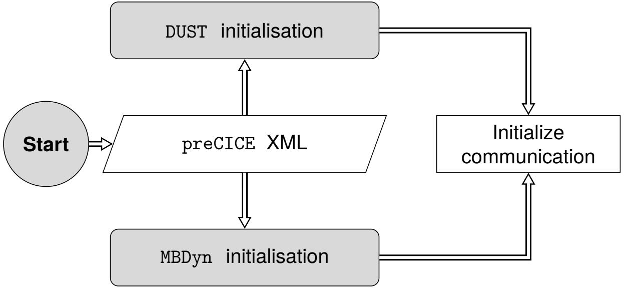

DUST initialisation
Start
preCICE XML
MBDyn initialisation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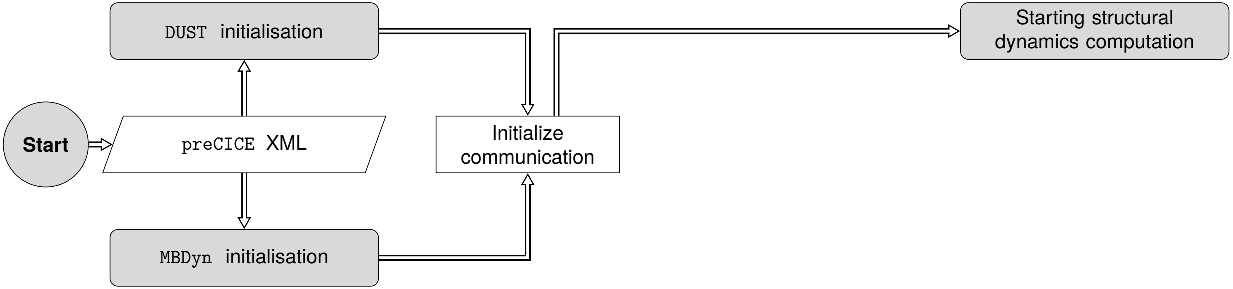
DUST initialisation
Starting structural
dynamics computation
Start
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Initialize
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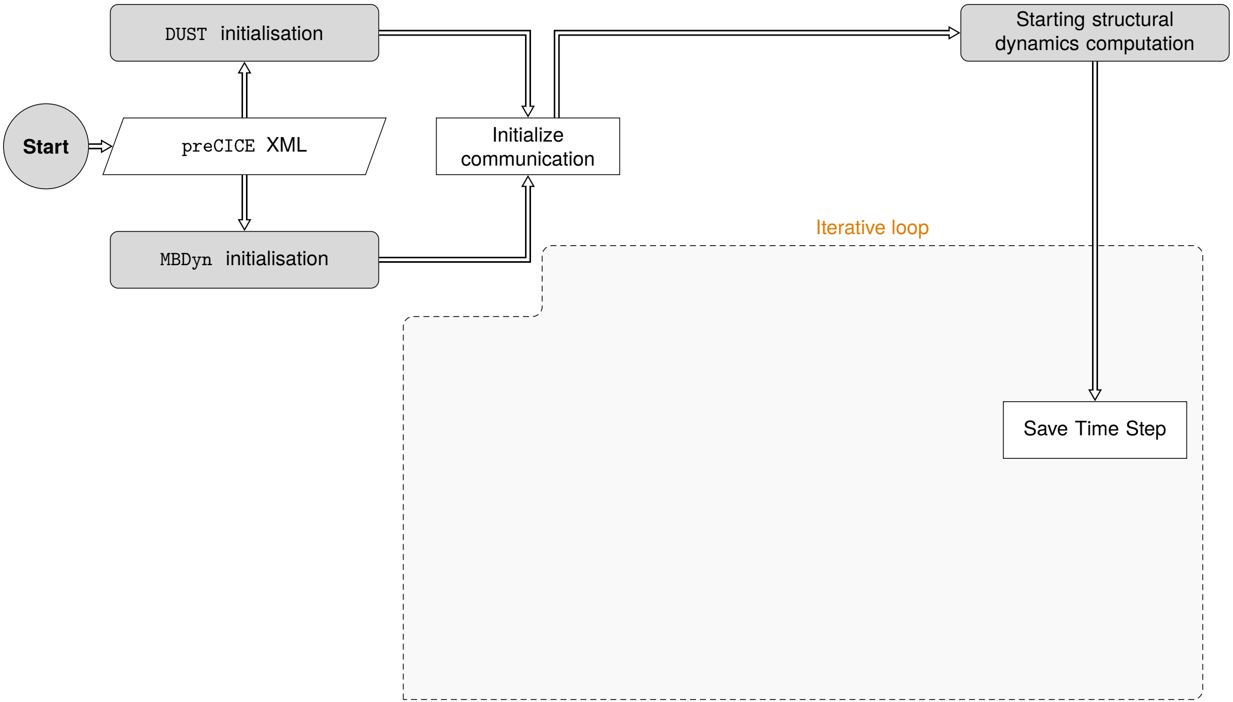
DUST initialisation
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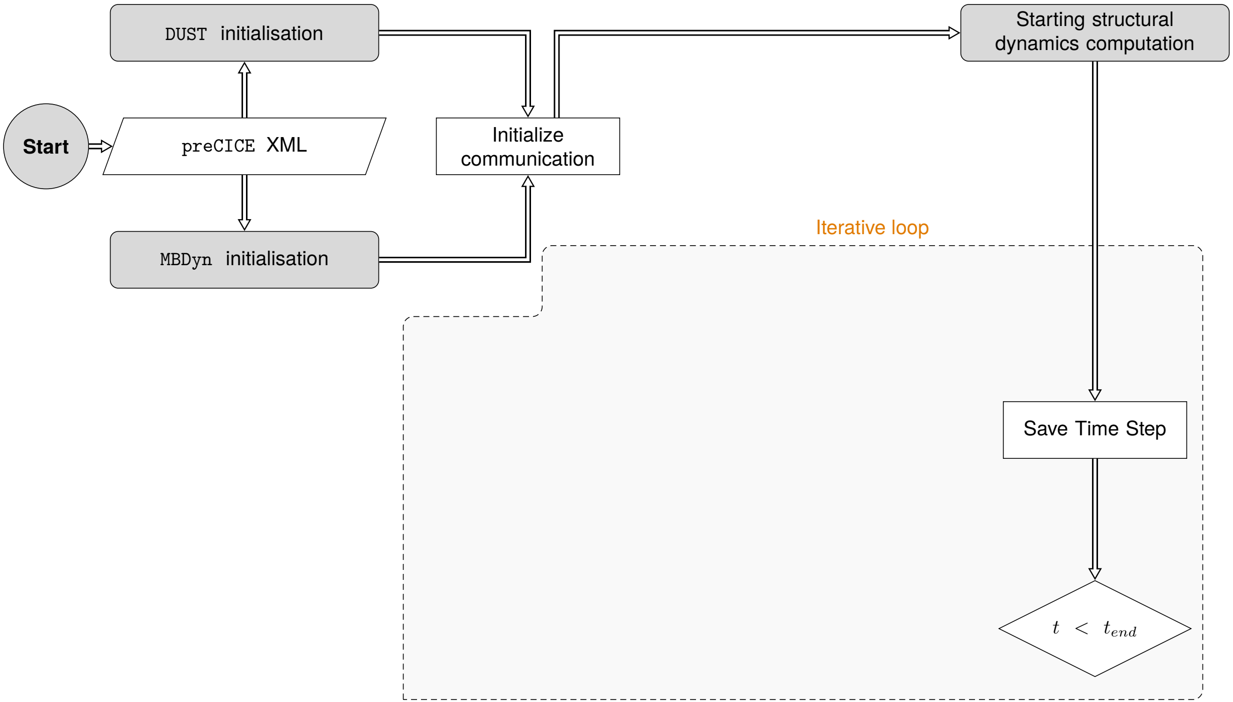
Initialize communication
Iterative loop
MBDyn initialisation
Save Time Step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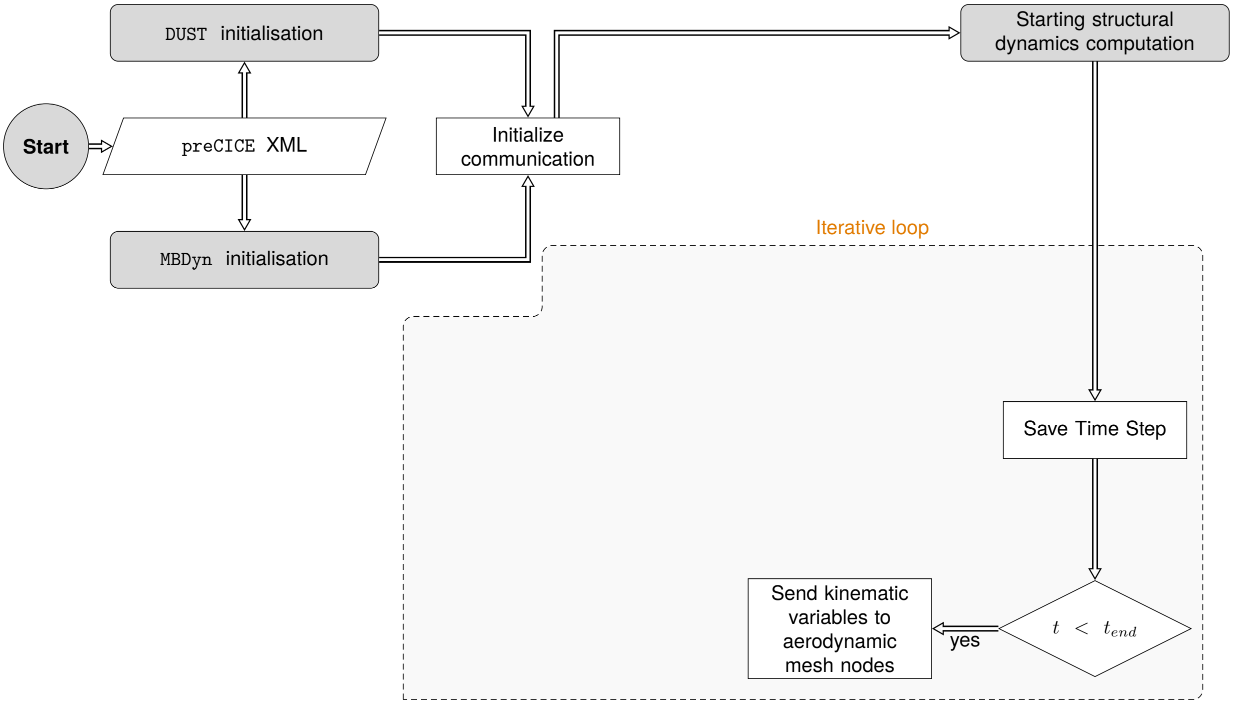
$t < t_{end}$


DUST initialisation
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Save Time Step
Send kinematic variables to aerodynamic mesh nodes
yes
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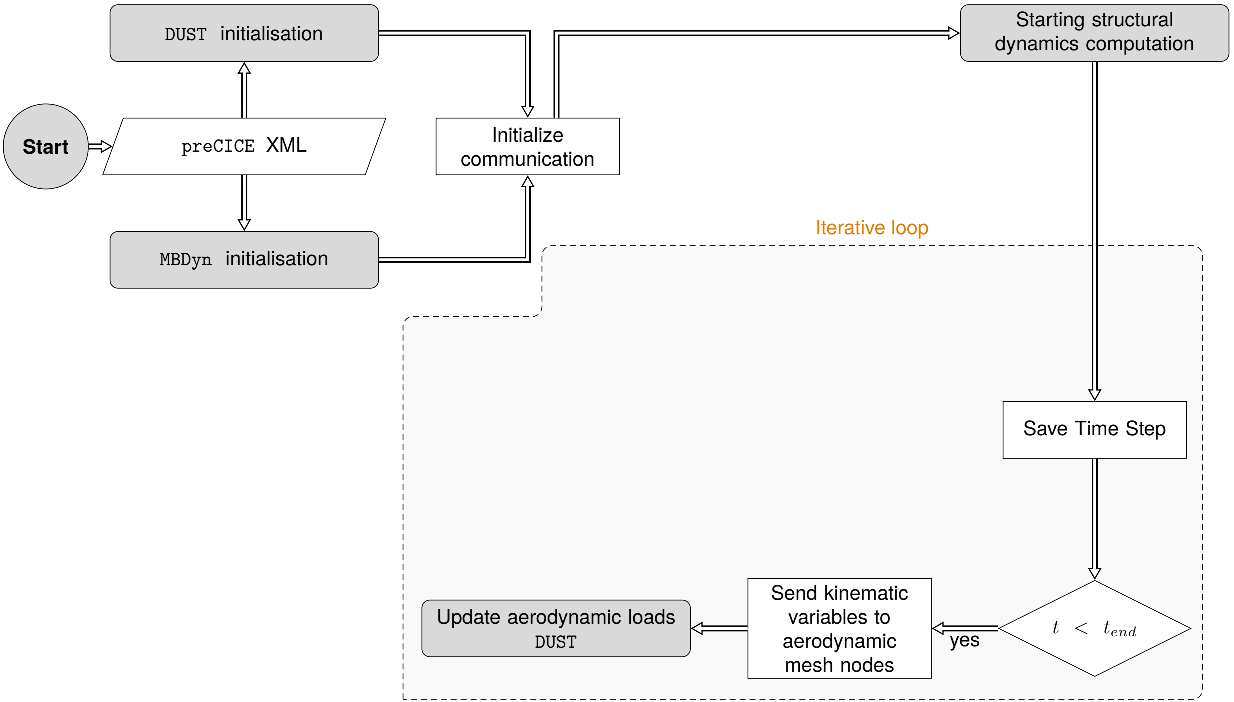

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Update aerodynamic loads DUST
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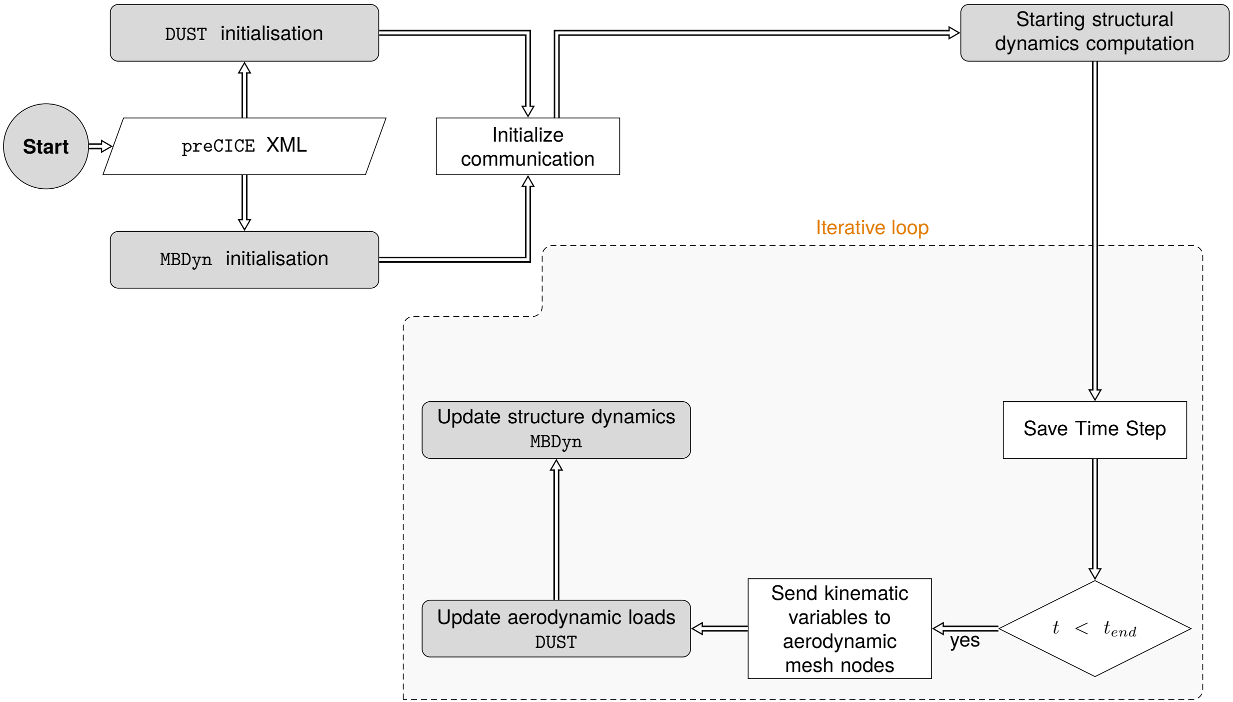
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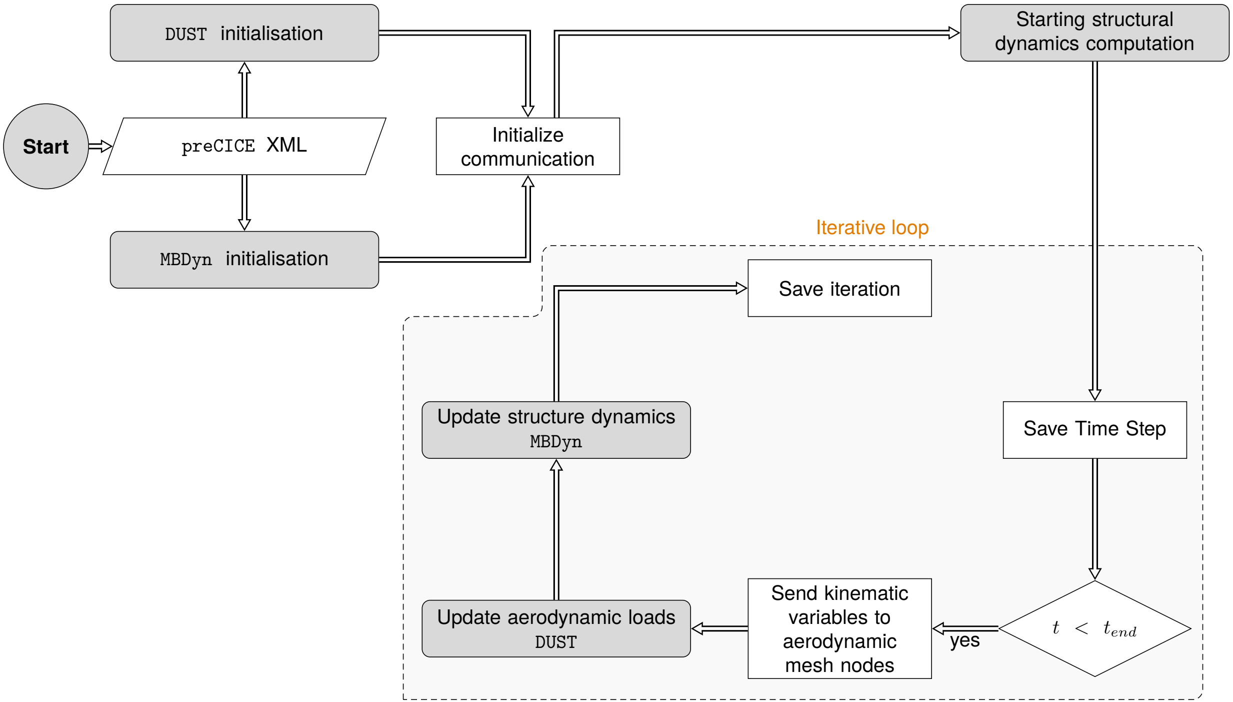
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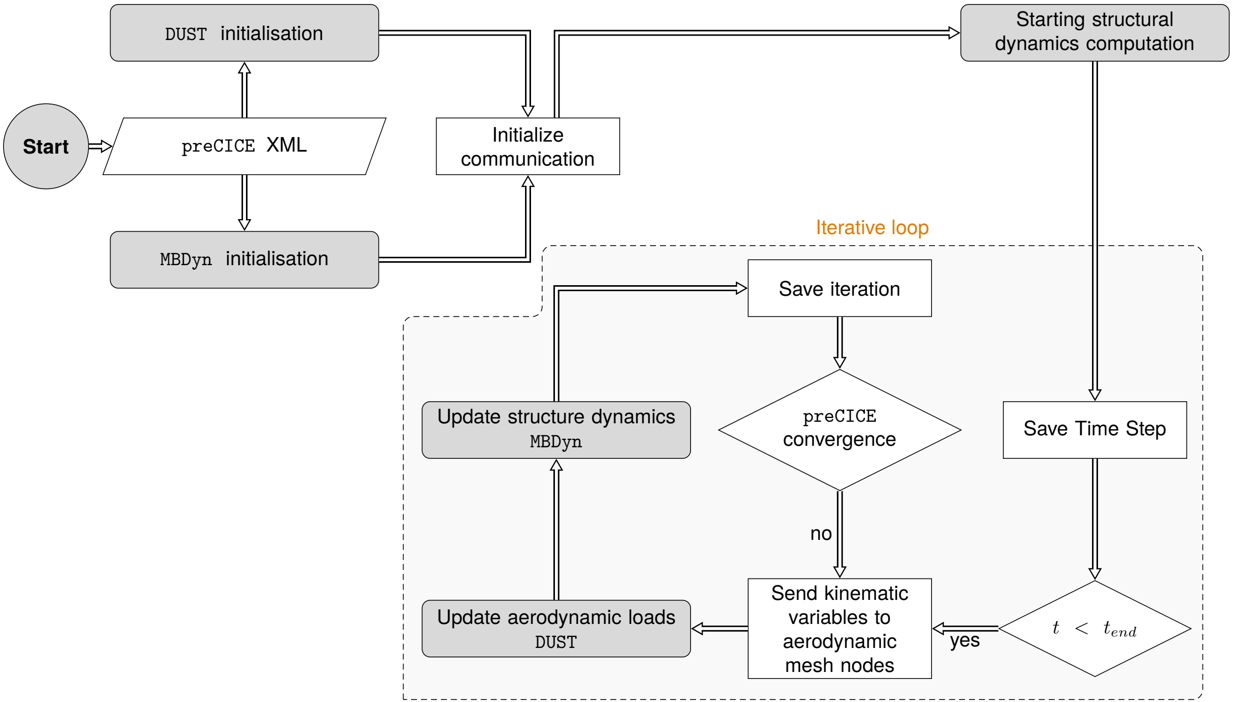
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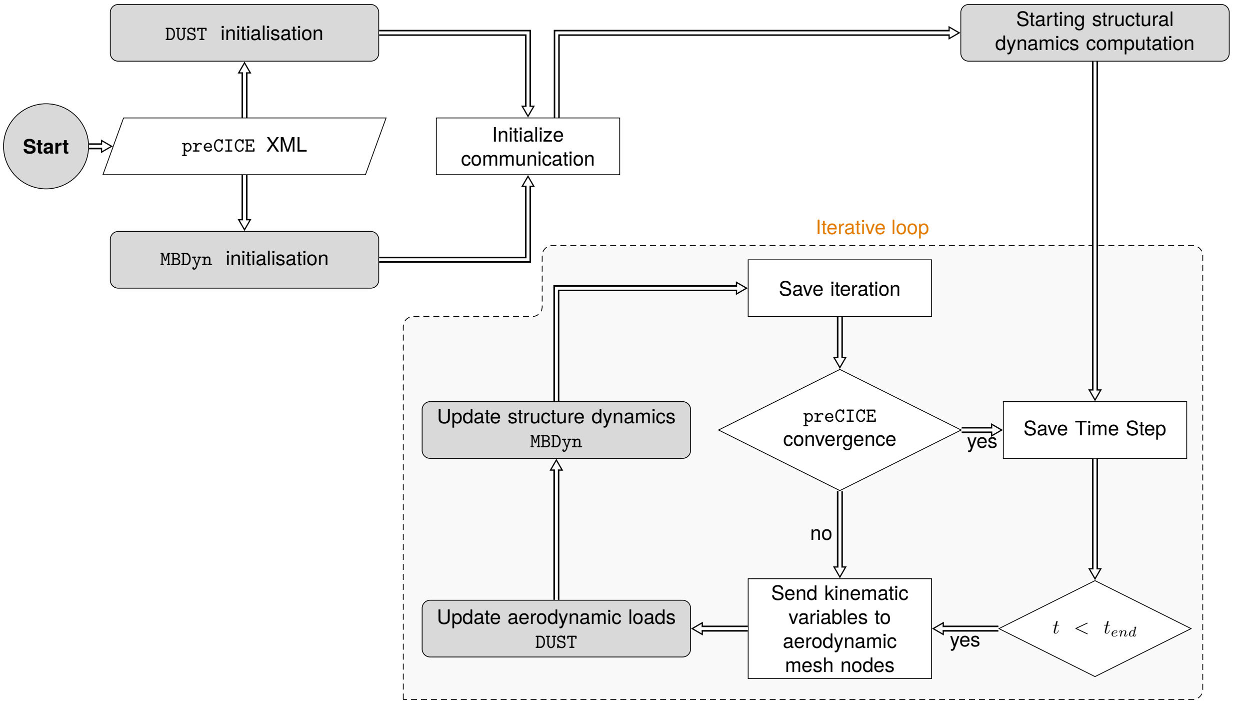
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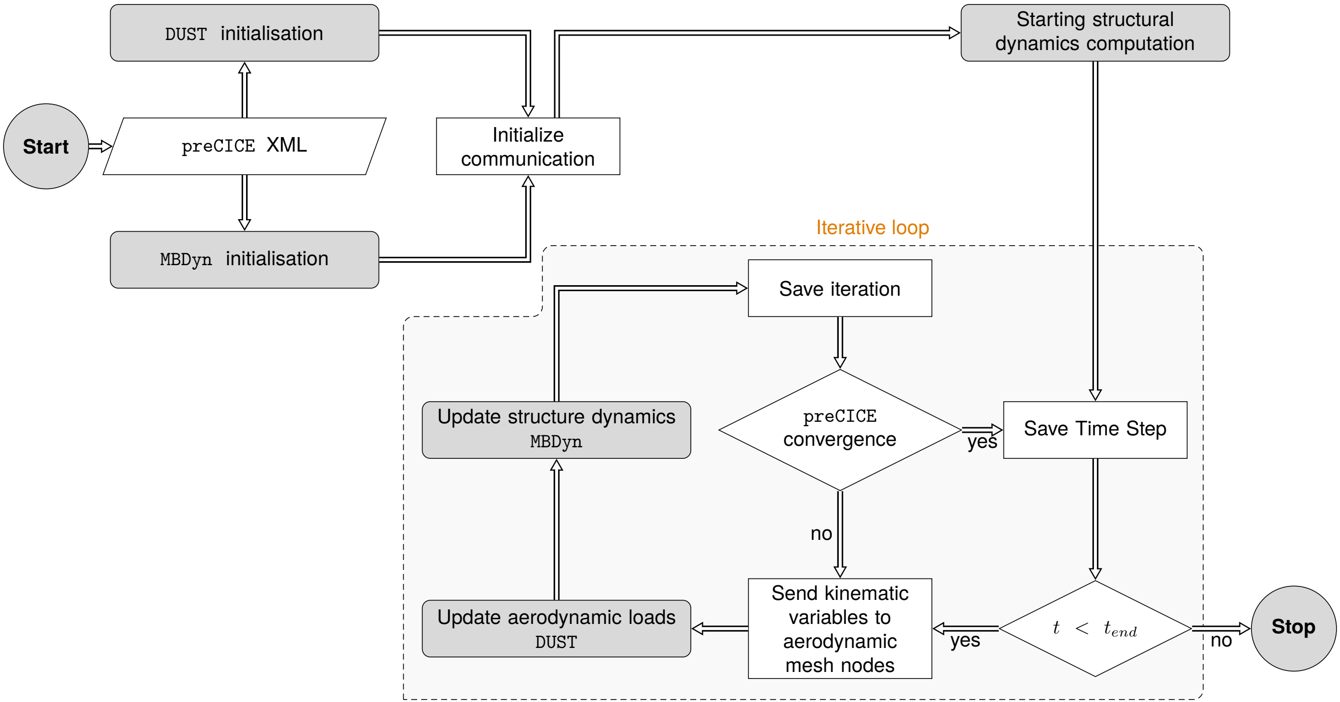
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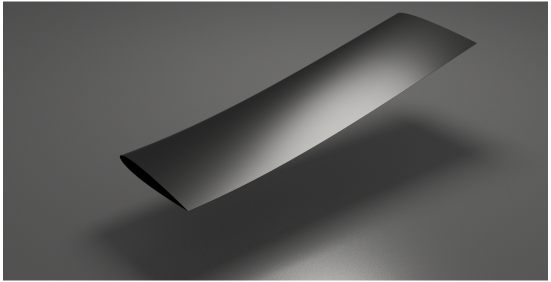
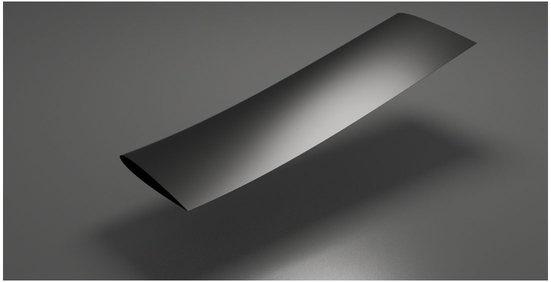
Stop

- Analysis Procedure



Wing properties			
Chord, c	1.8288 m	Mass per unit length	35.71 $\mathrm{kg\,m^{-1}}$
Half span	6.096 m	Moment of inertia	8.64 $\mathrm{kg\,m^{-1}}$
Elastic axis	$0.33 \cdot c$	Torsional stiffness	$0.99{\times}10^6$ $\mathrm{N\,m^2}$
Center of gravity	$0.43 \cdot c$	Bending stiffness	$9.77{\times}10^6$ $\mathrm{N\,m^2}$
Flight conditions			
Air density	1.020 $\mathrm{kg\,m^{-3}}$	Perturbation of AoA	0.05 deg



- Analysis Procedure
  1. Structural model: 4 non–linear finite volume `MBDyn` beams

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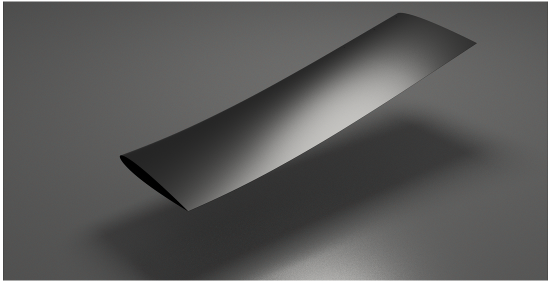

	Goland [1] Hz	*NASTRAN* Hz	`MBDyn` Hz
1^{st} *Bending*	7.66	7.66	**7.66**
1^{st} *Torsion*	15.24	15.24	**15.21**
2^{nd} *Bending*	38.80	38.59	**38.54**
2^{nd} *Torsion*	55.33	54.84	**54.79**

[a] Goland, M (1945)

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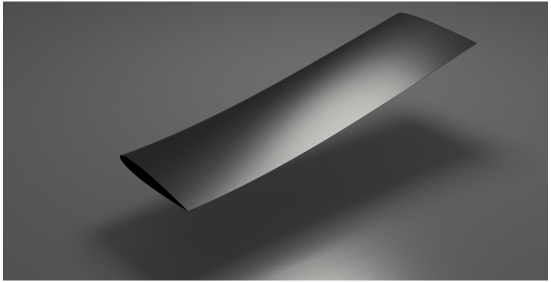

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- Analysis Procedure
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  3. Two types of aerodynamic elements were tested:
     - Vortex Lattice (vl): flat plate
     - 3D panels: maintain profile shape and thickness

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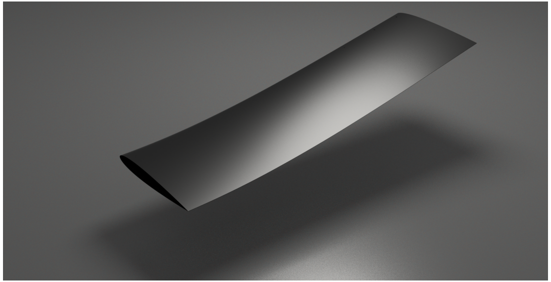

	Goland [1] Hz	*NASTRAN* Hz	*MBDyn* Hz
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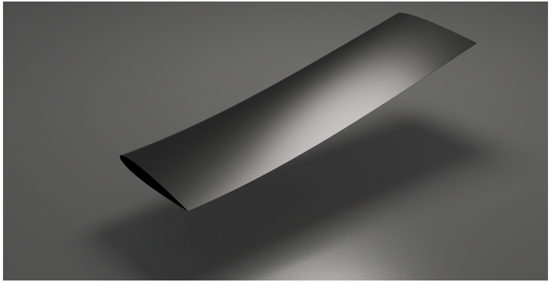

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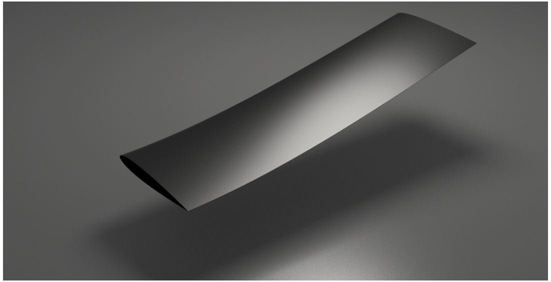

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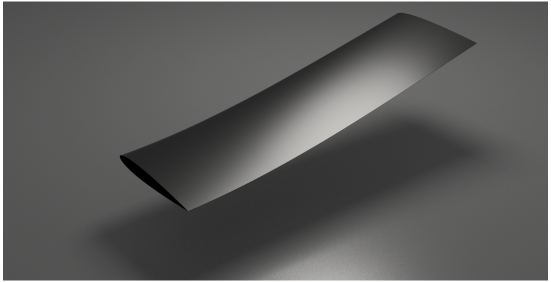

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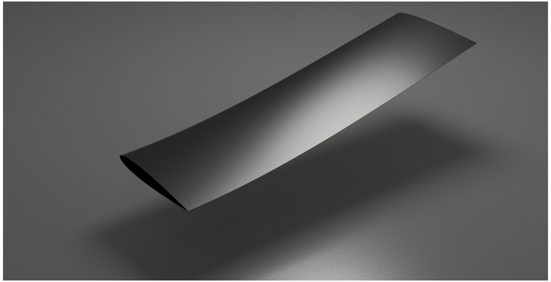

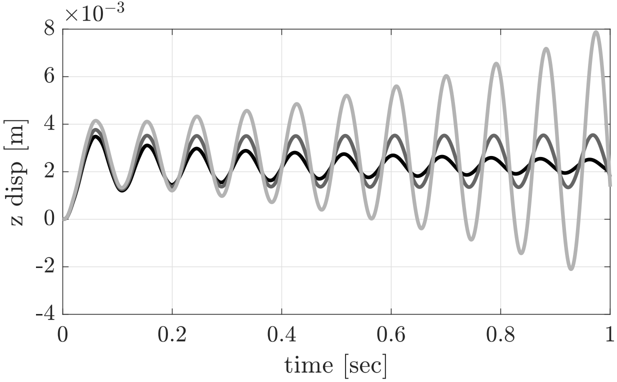

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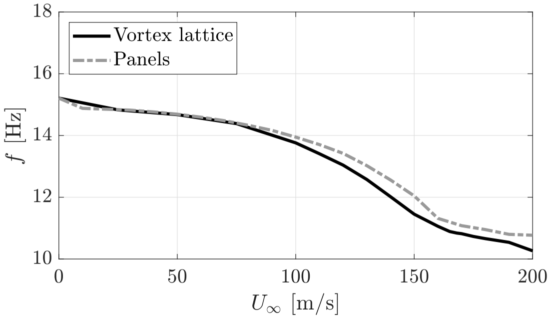
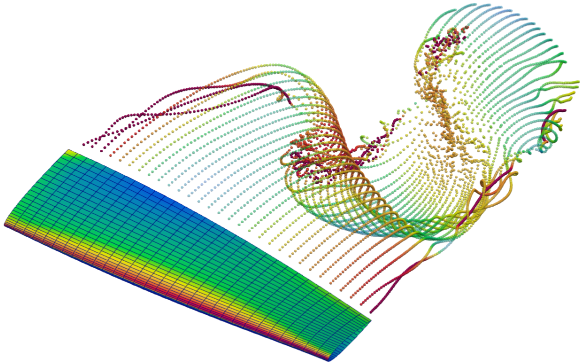
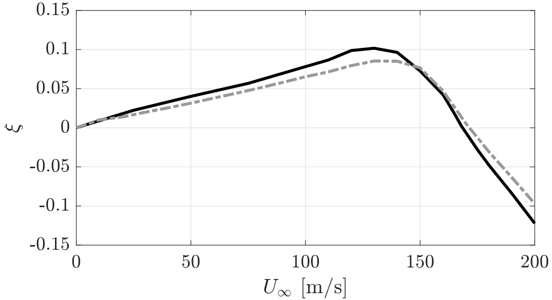
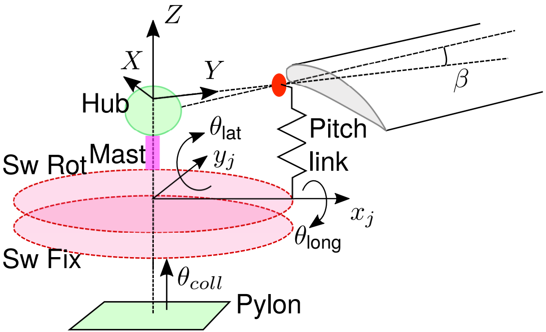
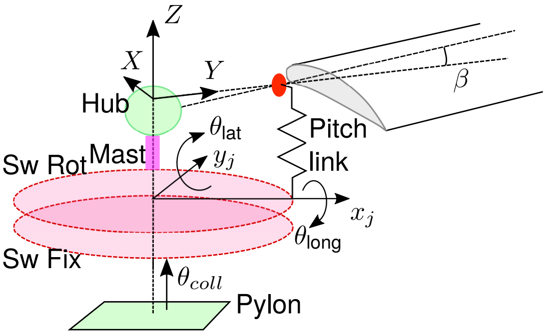






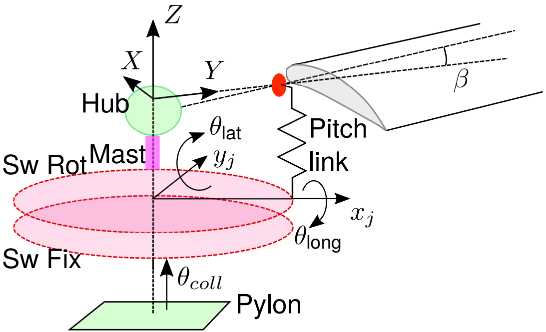
Author	*Model*	V_f m s^{-1}	f_f Hz
Goland and Luke	Analytical	137.2	11.25
Patil et al.	Intrinsic beam + strip theory	135.6	11.17
Wang et al.	ZAERO	174.3	-
Wang et al.	Intrinsic beam + UVLM	163.8	-
SHARP et al.	Displacement beam + UVLM	165	10.98
Present Work	DUST (vl)-MBDyn	168.2	10.84
Present Work	DUST(panel)-MBDyn	171.5	11.06


Z
X
Y
β
Hub
θ_{lat}
y_j
Pitch
link
Sw Rot
Mast
x_j
θ_{long}
Sw Fix
θ_{coll}
Pylon



Rotor Multibody Model

- 3 Rigid blades
- Gimballed rotor $\rightarrow$ rotation in the hub plane are allowed



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- 6 NACA 64-XXX series airfoil profiles for each blade
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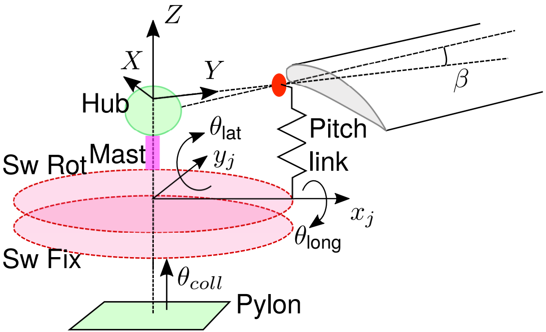

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Blade	3	
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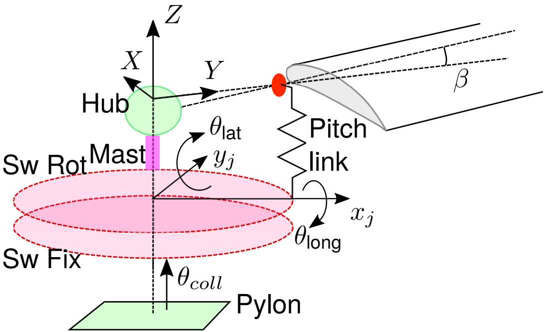
Radius	3.81	m
Precone β	2.5	deg
Chord	0.3556	m
Twist	45	deg
Nominal speed	589	RPM



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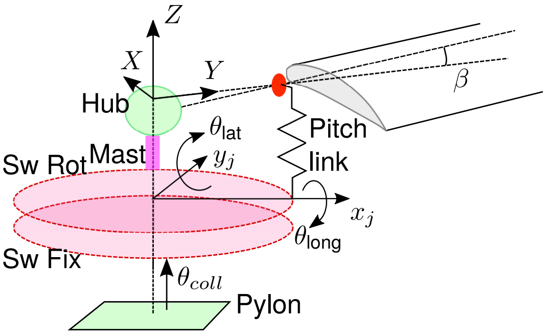
Fixed Wing Multibody Model

- Each component is associated to a rigid body
- 1 DOF → roll rotation



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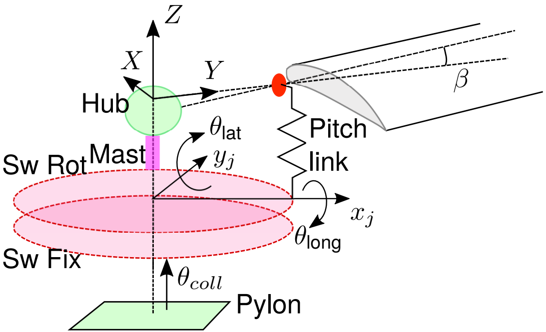

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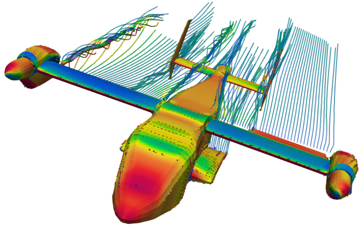
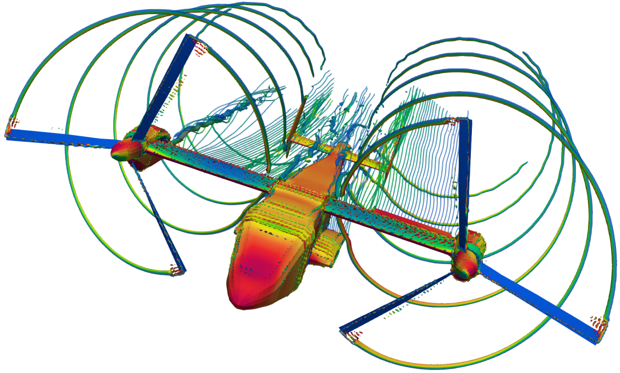
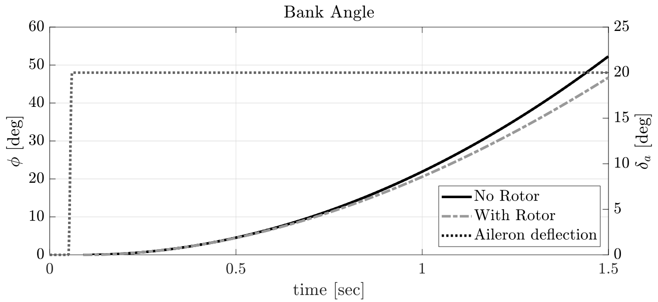
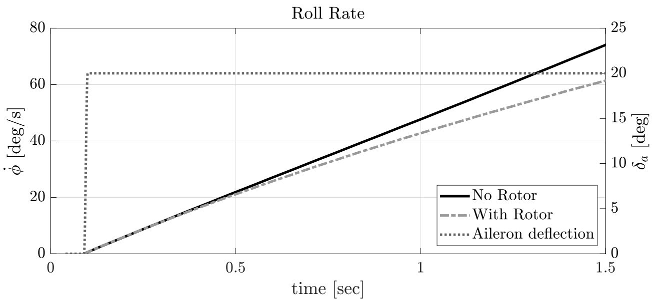
Wing data		
Aperture	4.90	m
Chord	1.601	m
Contr. Surf.	2	
Dihedral	2.5	deg
Sweep	-6.5	deg
Profile	NACA64A223	






Bank Angle
ϕ [deg]
δ_a [deg]
time [sec]
No Rotor
With Rotor
Aileron deflection


Roll Rate
$\dot{\phi}$ [deg/s]
δ_a [deg]
time [sec]
No Rotor
With Rotor
Aileron deflection

Conclusions

- A new aeroelastic solution has been proposed by joining the multibody solver `MBDyn` and the mid-fidelity aerodynamic tool `DUST` through the partitioned multi–physics coupling library `preCICE` .
- Aeroelastic validation has been conducted evaluating the Flutter stability boundary of Goland's wing
- The roll maneuver of a tiltrotor configuration has been considered evaluating the effect of the rotor's presence

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Developments

- Evaluate the reciprocal interaction between parts, for example tail shape ect . . .
- Simulate more realistic condition by allowing all 6 rigid DOF to the aircraft
- Evaluate the effect of the elasticity of the rotor and wing
- Perform whirl–flutter stability analysis

Thank you for your kind attention