Rotorcraft Icing Simulations and a CFD Analysis of Rotors in Hover/Rotor-Fuselage Interactions

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SAC Faye Storer, (2013), *Royal Air Force Search and Rescue helicopter with D Flight 202 Squadron*.
Available at: http://www.defenceimagery.mod.uk/fotoweb/fwbin/download.dll/45153802.jpg

OUTLINE

- **PhD**
  - Rotorcraft Icing
  - Simulation Framework
  - Challenges Involved
- **Hover Flight**
  - Current status
  - SU2 Simulations
- **Forward Flight Modelling**
  - Limitations
  - Blade Dynamics
- **Rotor-Fuselage Interaction**
  - Sliding Mesh Technique
  - AW609 Test
  - ERICA Test

Air Zermatt helicopter just before a rescue. - © Air Zermatt.
Available at: https://www.zermatt.ch/en/Media/Attractions/Air-Zermatt

Photo courtesy of Leonardo

ROTORCRAFT ICING ENVIRONMENT

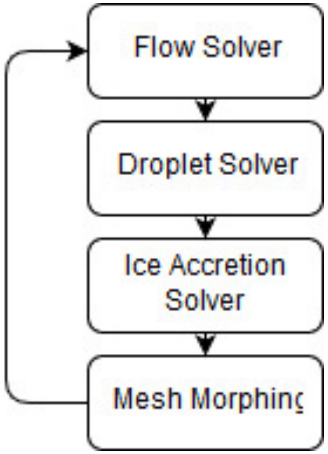
- Severely damaging consequences and a threat to flight safety
- Icing on the main rotor alters the blade geometry
  - Increased surface roughness leads to increased drag, reduction of lift and premature onset stall
  - These aerodynamic changes invariably have implications on the helicopter stability, flight condition, power and torque characteristics and component loading.
- Experimental and In-Flight testing
  - expensive both in terms of cost and time
- Simulations
  - increase safety
  - reduce in-flight accidents

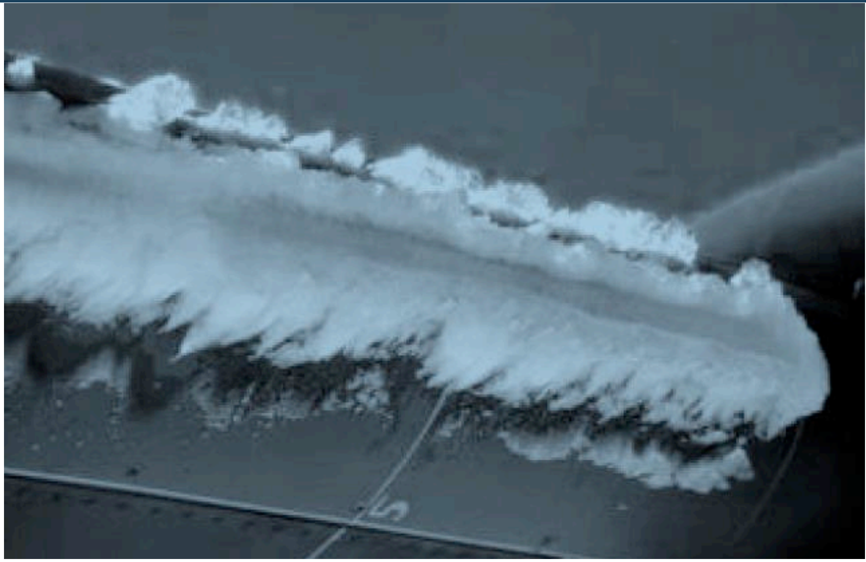
Source: J. D. Lee, R. Harding, and R. L. Palko, *Documentation of ice shapes on the main rotor of a uh-1h helicopter in hover*, 1984.

Simulation Framework

- Different meteorological conditions, means different ice shapes
- *Rime* ice
  - Lower temperatures
  - Characteristic *spearhead*
- *Glaze* ice
  - Higher temperatures
  - Characteristic *horns*
- Icing software needs to model all ice shapes

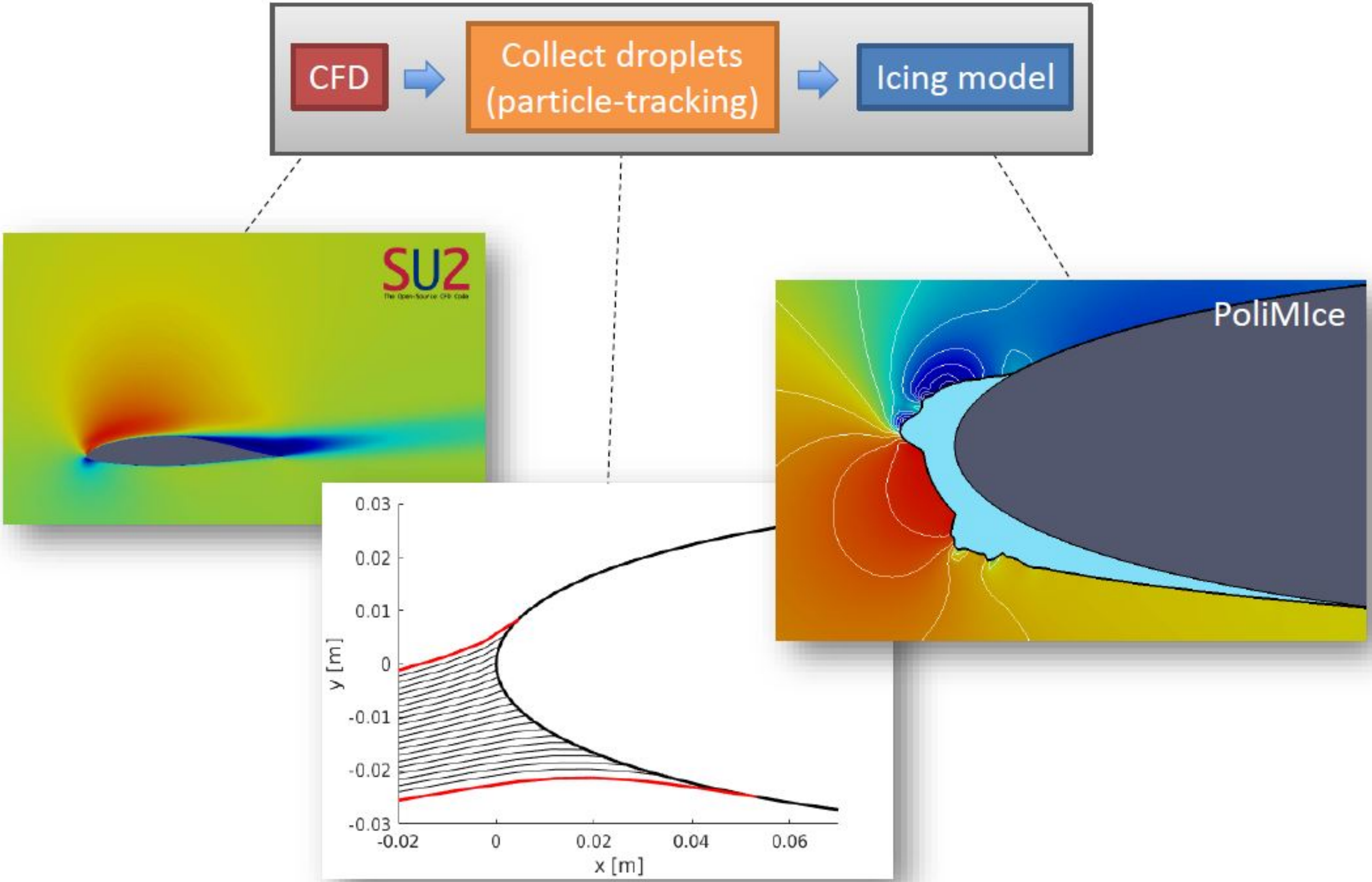
- Simulation framework





Source: NASA Glenn Research Center: https://www.nasa.gov/centers/glenn/home/index.html

SIMULATION FRAMEWORK



CHALLENGES INVOLVED

- Complex rotor geometry
  - Large mesh size due to it being an entirely 3-dimensional problem
  - Time consuming to mesh non-linearly twisted blades with varying radial airfoil design

- Flowfield Simulation
  - Large mesh size means large computational time
  - Need to validate flowfield to ensure correct ice accretion
  - Many rotorcraft flight conditions; hover, forward flight, climb and descent
  - Many rotorcraft configurations; main-rotor/tail-rotor, coaxial, tandem, tilt-rotor, intermeshing, etc.

- Droplet Collection Efficiency
  - Lagrangian particle tracking in 3D requires a large amount of droplets
  - Particle tracking over multiple zones

Hover Flight

- Hover flight represents the simplest flight condition
  - Blades experience no blade normal velocity
  - Blade motion can be considered constant with azimuth angle
  - Essentially can be considered as a steady state problem
- Palacios et al. results using SU2 for hover flight [1]
  - Validated against the Caradonna and Tung. Experiments [2]
  - Used rotating frame method
  - Steady simulation
- Rotorcraft icing test cases of [3, 4]
  - Stipulates a slight inflow for water droplet-blade interaction purposes during hover
  - Forward flight requires a significant inflow velocity
  - Both cases should hence be considered as unsteady
  - Further testing required

[1] Palacios, Francisco, et al. *Stanford university unstructured (SU2): Analysis and design technology for turbulent flows*. *52nd Aerospace Sciences Meeting*. 2014.

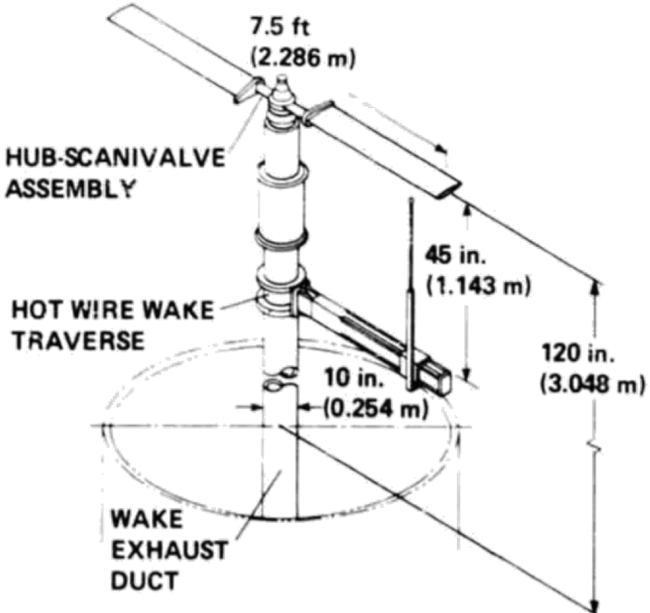
[2] Caradonna, Francis X., and Chee Tung. *Experimental and analytical studies of a model helicopter rotor in hover.* 1981.

[3] Fortin, Guy, and Jean Perron. *Spinning rotor blade tests in icing wind tunnel*. 1st AIAA Atmospheric and Space Environments Conference. 2009

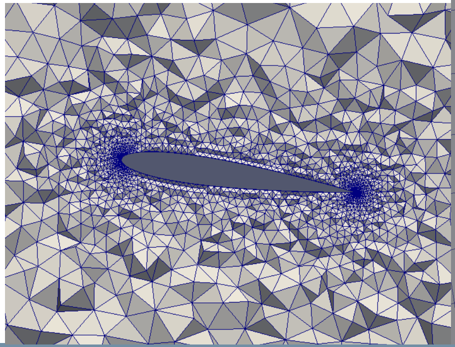
[4] Lee, J.D., Harding, R., Palko, R.L. *Documentation of Ice Shapes on the Main Rotor of a UH-1H Helicopter in Hover*, NASA CR 168332, Lewis Research Center, 1983.

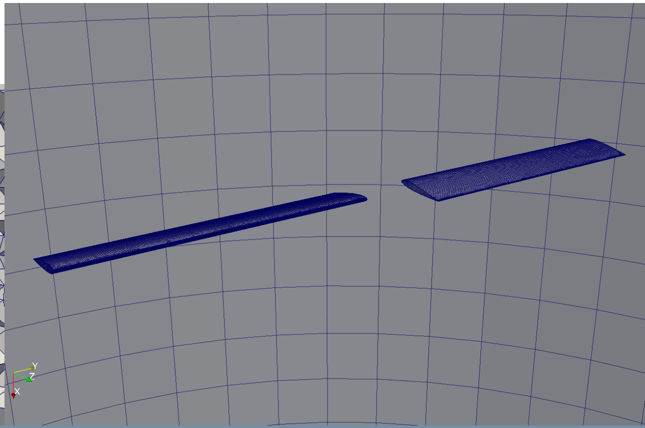
Hover Flight

- Caradonna and Tung. Experiment
  - 32 experiments; varying collective and rotational speed
  - Blade pressure coefficients well documented
  - 3 tests cases chosen:
    - 0 and 8 degrees collective
    - low Mach tip and high Mach tip numbers
- Method
  - NS equations are solved in a rotating reference frame
  - S-A turbulence model
  - Dual time stepping-2nd order
  - ROE convective numerical method
  - 2nd order upwind MUSCL scheme
  - Euler implicit time discretization
- Mesh
  - 9 million cells: ICEM CFD software
  - y+ < 1, 20 boundary layers
  - radius = 1.143 m, chord = 0.19m

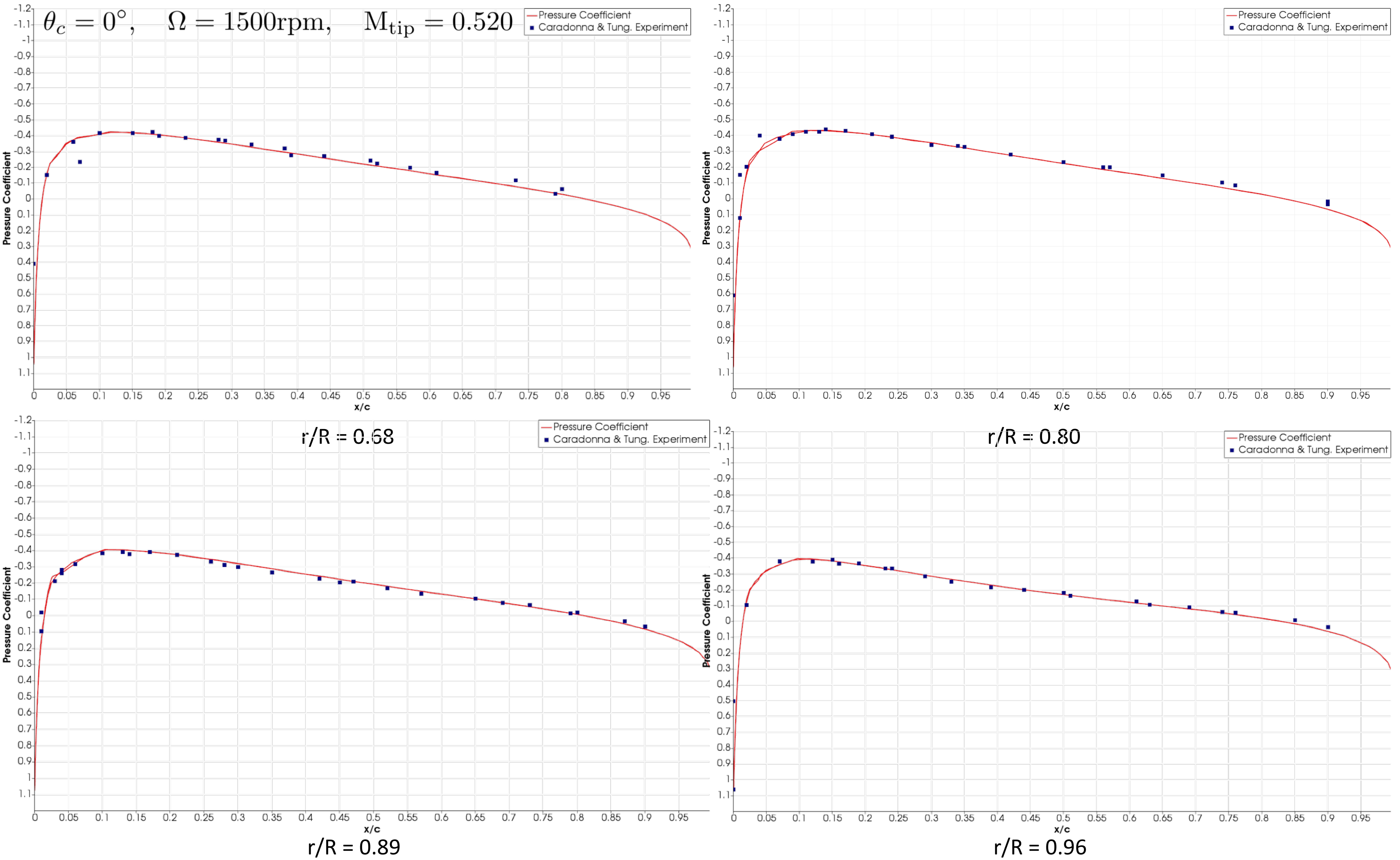


Source: Caradonna, Francis X., and Chee Tung. *Experimental and analytical studies of a model helicopter rotor in hover.* 1981.

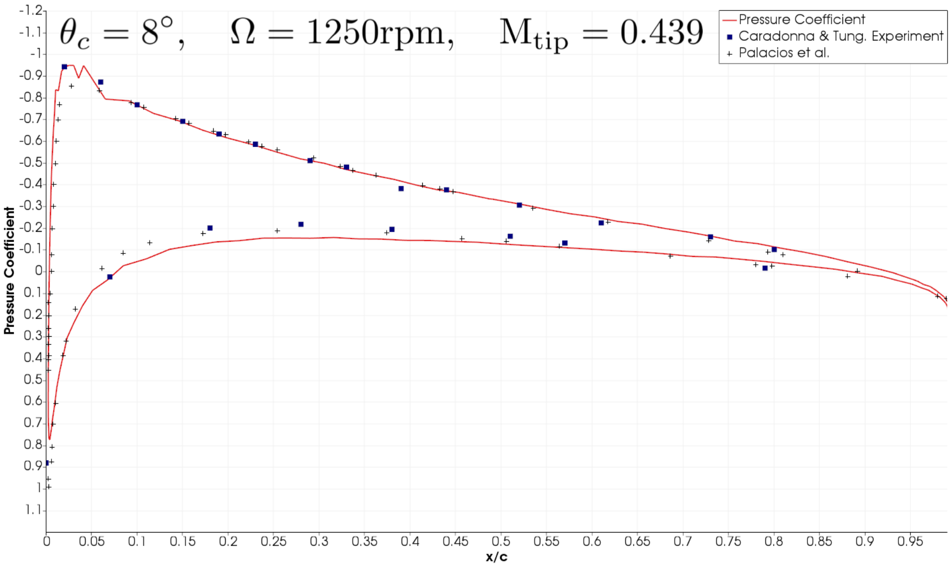


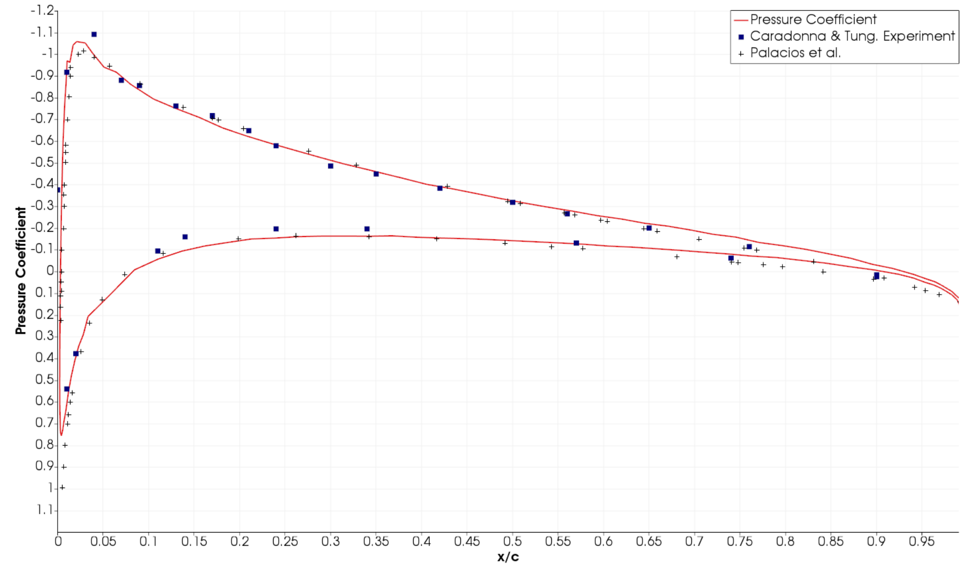


Hover Flight



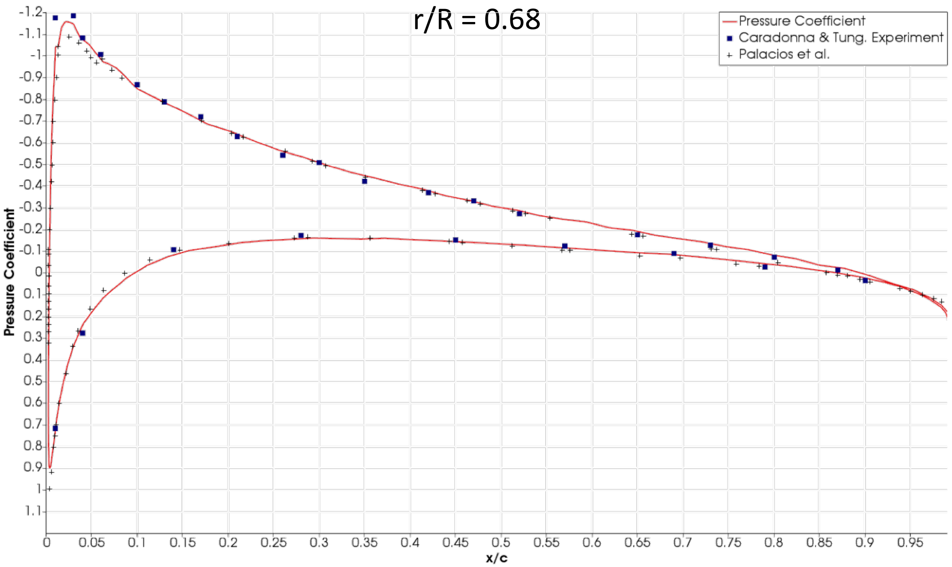
HOVER FLIGHT

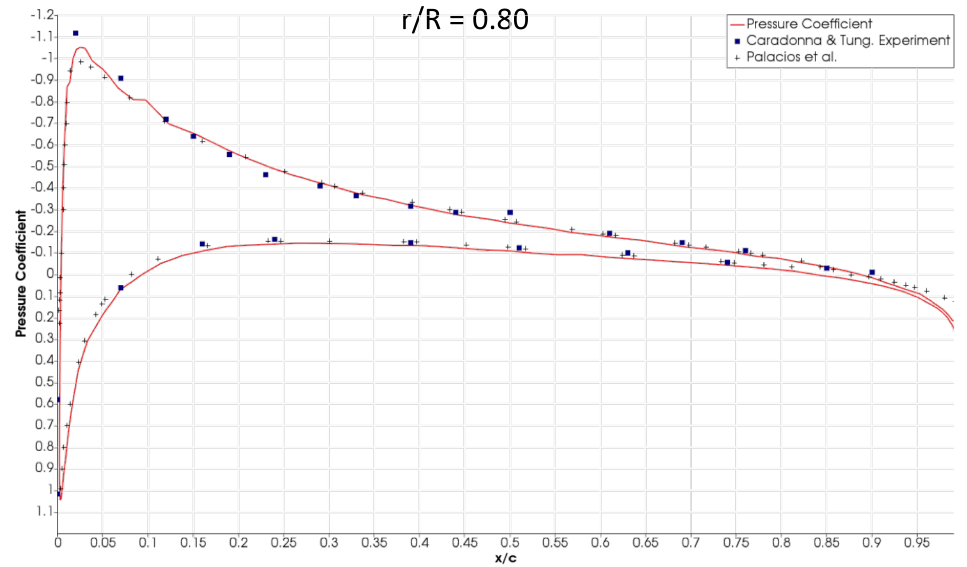




r/R = 0.68

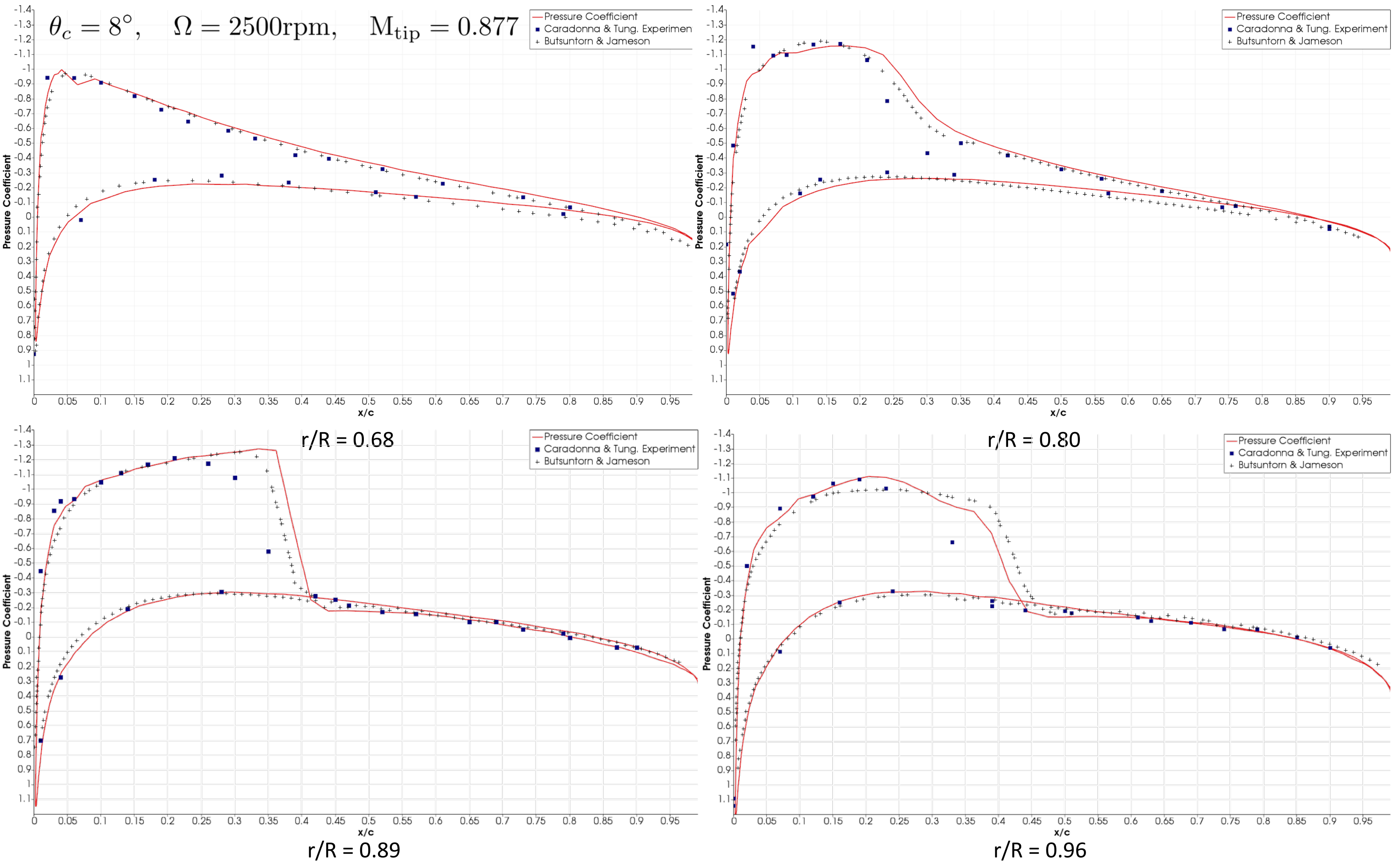
r/R = 0.80





r/R = 0.89

r/R = 0.96


$\theta_c = 8°, \quad \Omega = 2500\text{rpm}, \quad M_{tip} = 0.877$
Pressure Coefficient
Caradonna & Tung, Experimen
Butsuntorn & Jameson
Pressure Coefficient
x/c
r/R = 0.68
r/R = 0.80
r/R = 0.89
r/R = 0.96

FORWARD FLIGHT MODELLING

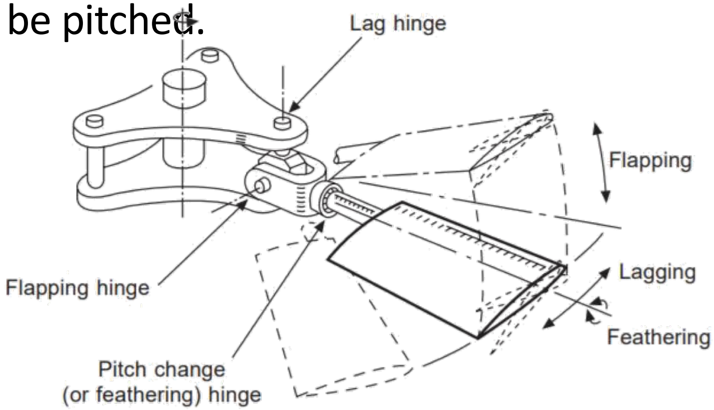
- In forward flight, the blades experience a blade normal velocity which depends on the azimuthal position

$$M_n(\psi) = M_{tip}\frac{r}{R} + M_\infty \sin\psi = M_{tip}\left(\frac{r}{R} + \mu\sin\psi\right)$$

where $\mu = \mathrm{M}_\infty/\mathrm{M}_{\mathrm{tip}}$ is the *advance ratio* of the rotor

- Hinges introduced eliminating the rolling moment which arises in forward flight. The flapping hinge allows the blade to flap i.e. to move in a plane containing the blade and shaft. Flapping causes large Coriolis moments in the plane of rotation and the lag hinge is provided to relieve these moments. Lastly the pitching hinge allows the blade to be pitched.

- The rotation, flapping, lead-lag and pitch angles are not yet possible to input into SU2



Source: Bramwell, Anthony RS, David Balmford, and George Done. *Bramwell's helicopter dynamics*. Elsevier, 2001

$$\psi = \omega t$$

$$\beta(\psi) = \beta_0 - \beta_{1s}\sin(\psi) - \beta_{1c}\cos(\psi) - \beta_{2s}\sin(2\psi) - \beta_{2c}\cos(2\psi) - \ldots$$

$$\delta(\psi) = \delta_0 - \delta_{1s}\sin(\psi) - \delta_{1c}\cos(\psi) - \delta_{2s}\sin(2\psi) - \delta_{2c}\cos(2\psi) - \ldots$$

$$\theta(\psi) = \theta_0 - \theta_{1s}\sin(\psi) - \theta_{1c}\cos(\psi) - \theta_{2s}\sin(2\psi) - \theta_{2c}\cos(2\psi) - \ldots$$

Forward Flight Modelling

- The following transformation matrices can then be introduced

$$C_{\mathrm{rot}} = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad C_{\mathrm{flap}} = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix}$$

$$C_{\mathrm{lag}} = \begin{pmatrix} \cos\delta & -\sin\delta & 0 \\ \sin\delta & cos\delta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad C_{\mathrm{pitch}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

- The time derivatives can then be found and assuming a constant rotation rate the flap, lead-lag and pitch angles can be written as

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = \omega\frac{\mathrm{d}\beta}{\mathrm{d}\psi}, \qquad \frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega\frac{\mathrm{d}\delta}{\mathrm{d}\psi}, \qquad \frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega\frac{\mathrm{d}\theta}{\mathrm{d}\psi}$$

Forward Flight Modelling

- The coordinates of a point *P* in the blade fixed system in terms of its co-ordinates in the helicopter frame of reference after rotation, flapping, lead-lag and pitching become

$$\vec{x}_P = C_{\mathrm{rot}} C_{\mathrm{flap}} C_{\mathrm{lag}} C_{\mathrm{pitch}} \left(\vec{x}_P - \vec{x}_{pitch} \right) + C_{\mathrm{rot}} C_{\mathrm{flap}} C_{\mathrm{lag}} \left(\vec{x}_{pitch} - \vec{x}_{lag} \right) + C_{\mathrm{rot}} C_{\mathrm{flap}} \left(\vec{x}_{lag} - \vec{x}_{flap} \right) + C_{\mathrm{rot}} \vec{x}_{flap}$$

- Where $\vec{x}_{flap}, \vec{x}_{lag}, \vec{x}_{pitch}$ define the locations of the flap hinge, lead-lag hinge and the centre of pitch. The Velocity of *P* in terms of the helicopter-fixed frame of reference is then

$$\frac{\mathrm{d}\vec{x}_P}{\mathrm{d}t} = \frac{\mathrm{d}C_{\mathrm{rot}} C_{\mathrm{flap}} C_{\mathrm{lag}} C_{\mathrm{pitch}}}{\mathrm{d}t} \left(\vec{x}_P - \vec{x}_{pitch} \right) + \frac{\mathrm{d}C_{\mathrm{rot}} C_{\mathrm{flap}} C_{\mathrm{lag}}}{\mathrm{d}t} \left(\vec{x}_{pitch} - \vec{x}_{lag} \right) + \frac{\mathrm{d}C_{\mathrm{rot}} C_{\mathrm{flap}}}{\mathrm{d}t} \left(\vec{x}_{lag} - \vec{x}_{flap} \right) + \frac{\mathrm{d}C_{\mathrm{rot}}}{\mathrm{d}t} \vec{x}_{flap}$$

- Using these equations the position and velocity of any point *P* in the helicopter-fixed frame of reference can be expressed as a function of the azimuth ψ

Forward Flight Modelling

- Rotational movement introduces large deformations hence rigid motion rotating the whole grid would be most appropriate in SU2

- On the contrary, flapping, lead-lag and pitching motion in SU2 should be defined with deforming mesh techniques

- This technique is supported including an adaptive sliding mesh technique by [9]

- Possible SU2 configuration file option for implementation:

```
Grid_Movement        = Rotorcraft_Motion
Rotational_Speed     = ω
Flap_motion          = β(ψ) = β_0 − β_1s sin(ψ) − β_1c cos(ψ) − ...
Lag_motion           = δ(ψ) = δ_0 − δ_1s sin(ψ) − δ_1c cos(ψ) − ...
Pitching_motion      = θ(ψ) = θ_0 − θ_1s sin(ψ) − θ_1c cos(ψ) − ...
Flap_hinge           = x⃗_flap
Lag_hinge            = x⃗_lag
Pitch_hinge          = x⃗_pitch
Rotation_Center      = x⃗_rot
```

$$\beta(\psi) = \beta_0 - \beta_{1s}\sin(\psi) - \beta_{1c}\cos(\psi) - \ldots$$

$$\delta(\psi) = \delta_0 - \delta_{1s}\sin(\psi) - \delta_{1c}\cos(\psi) - \ldots$$

$$\theta(\psi) = \theta_0 - \theta_{1s}\sin(\psi) - \theta_{1c}\cos(\psi) - \ldots$$

[9] Park, Young Min, and Oh Joon Kwon. "Simulation of unsteady rotor flow field using unstructured adaptive sliding meshes." *Journal of the American Helicopter Society* 49.4 (2004): 391-400.

Rotor-Fuselage Interaction

- Rotor-Fuselage interactional aerodynamics
  - Hugely important to the design and performance analysis of helicopters
  - Difficult to simulate due to such complex configurations

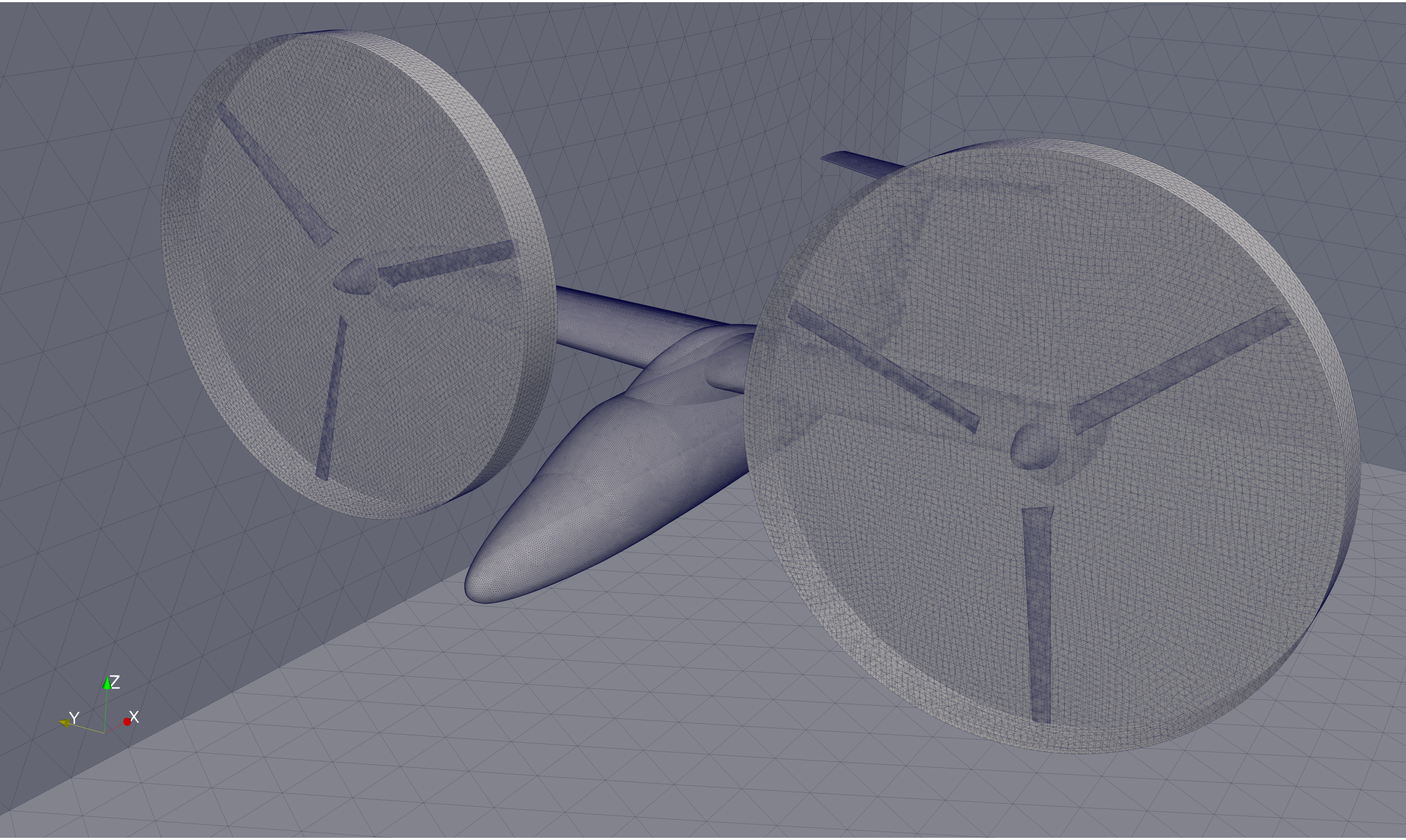
- Sliding mesh technique
  - Introduced to account for the movement of the rotor whilst enabling the fuselage to remain stationary
  - Technique used based on Kline, Sanchez and later Gori
- The AW609 tilt-rotor
  - Demonstrated during forward flight condition
  - Clockwise and Anticlockwise rotation involved
  - Interest due to its FIPS
  - Class of rotorcraft considered the next generation

Photo courtesy of Leonardo

[5] Economon, Thomas, Francisco Palacios, and Juan Alonso. "Unsteady aerodynamic design on unstructured meshes with sliding interfaces." *51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*. 2013.

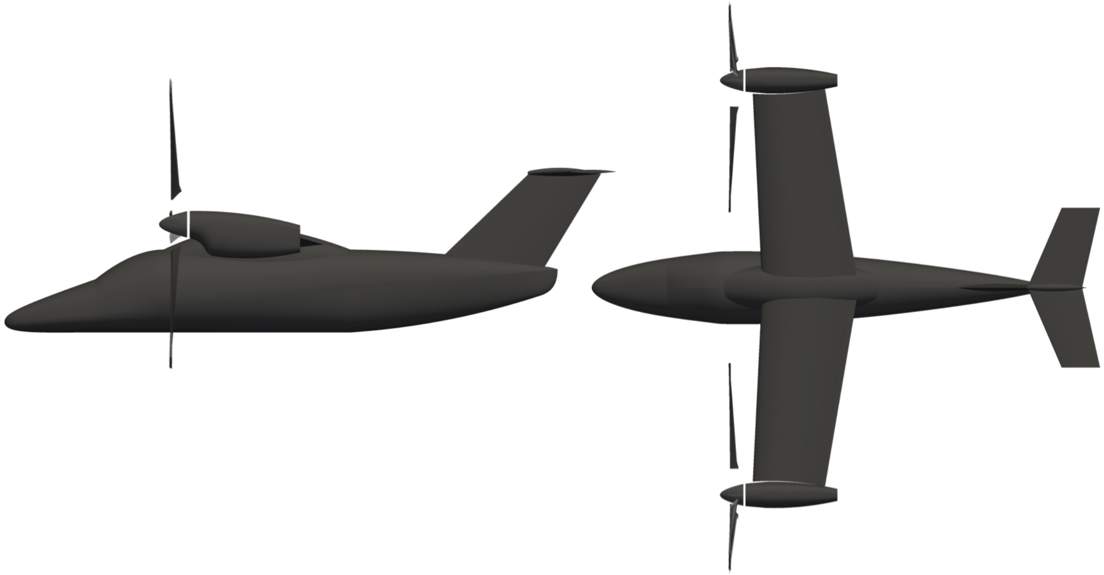
[6] Giulio Gori, Edwin van der Weide and Alberto Guardone“On Conservation in Compressible Flow Simulations Using Sliding Mesh Coupling.” Coupled Problems in Science and Engineering VII .2017.

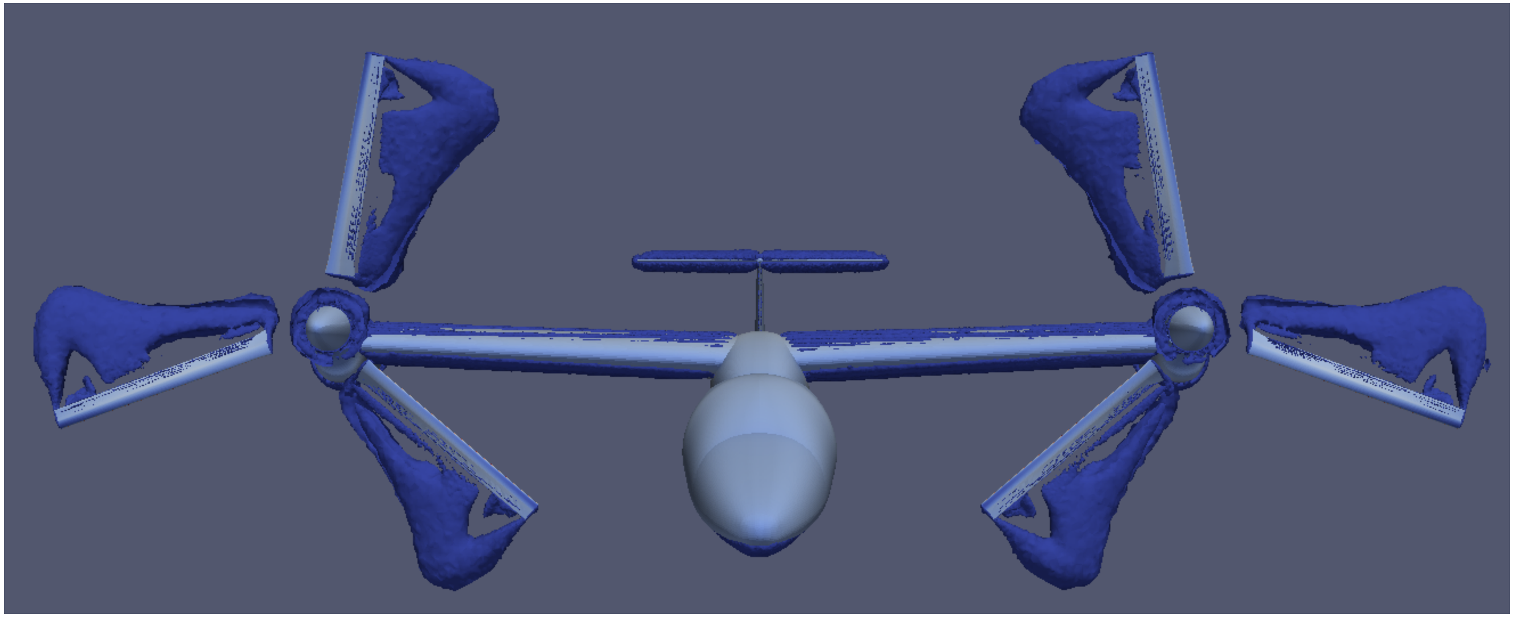
Rotor-Fuselage Interaction



Rotor-Fuselage Interaction

- Complex geometry
  - Rotor
  - Wing
  - Fuselage
- Q-criterion flow visualisation
- Multiple zones

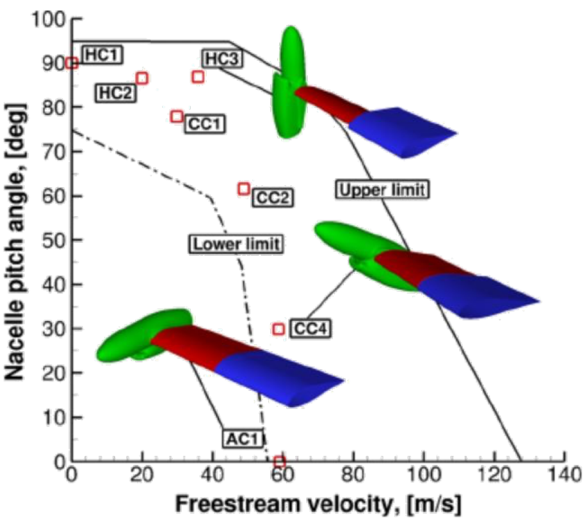




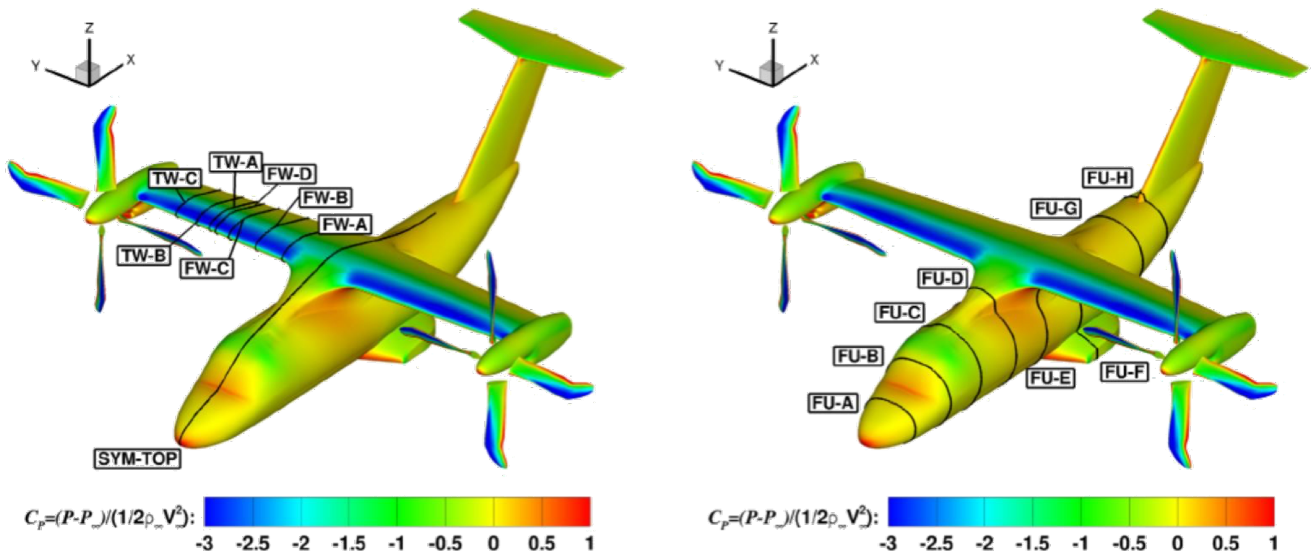
Rotor-Fuselage Interaction

- The development of the European innovative tiltrotor aircraft design **ERICA** [6] (**E**nhanced **R**otorcraft **I**nnovative **C**oncept **A**chievement) has been the subject of several European Community funded research projects in the past years [7, 8]

- Provides different experimental flight configurations corresponding to aeroplane, transition corridor, and helicopter modes with pressure profile comparisons on the fuselage, fixed-wing and tiltable-wing



Source: De Bruin and Schneider. *A discussion of measured static and dynamic rotor loads during testing of the ERICA tilt-wing rotorcraft configuration in DNW-LLF wind tunnel*. 2014.



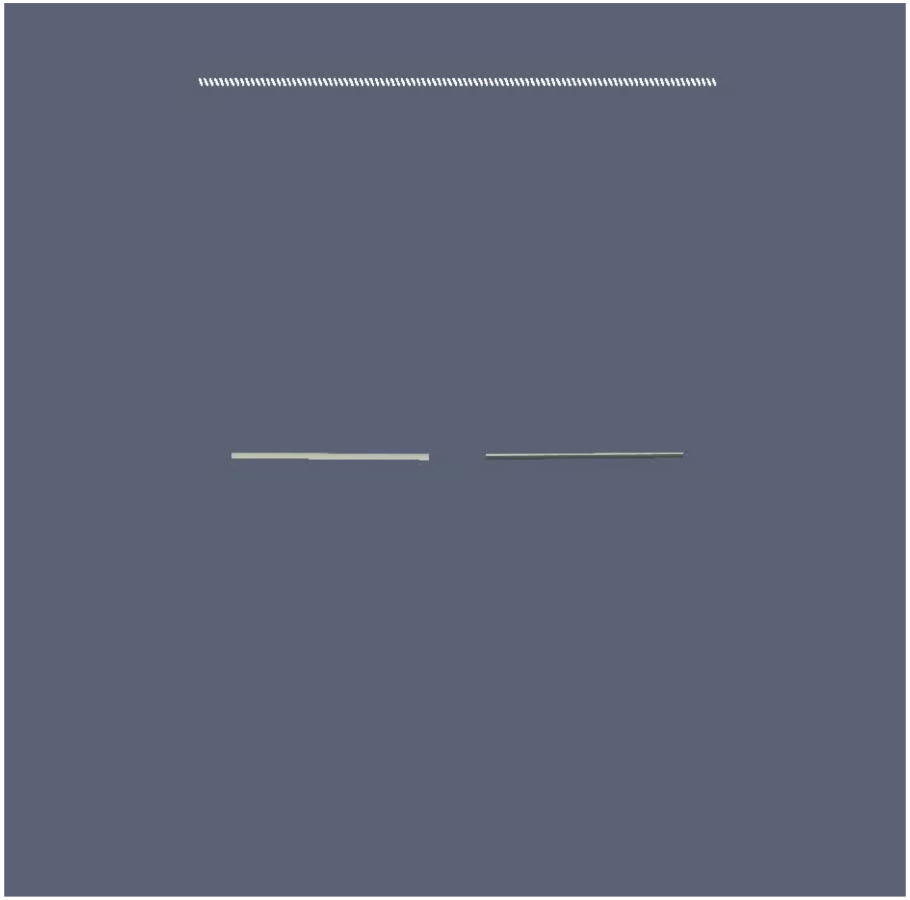
Source: Garcia, Antonio Jimenez, and George N. Barakos. "Numerical simulations on the ERICA tiltrotor." *Aerospace Science and Technology* 64 (2017): 171-191.

[6] Alli, P. *Erica: The European Tiltrotor. Design and Critical Technology Projects. AIAA International Air and Space Symposium and Exposition: The Next 100 Years*. 2005.

[7] Philipsen, I., and S. Heinrich. "Test report on measurements on the NICETRIP large-scale powered model in DNW-LLF." (2013).

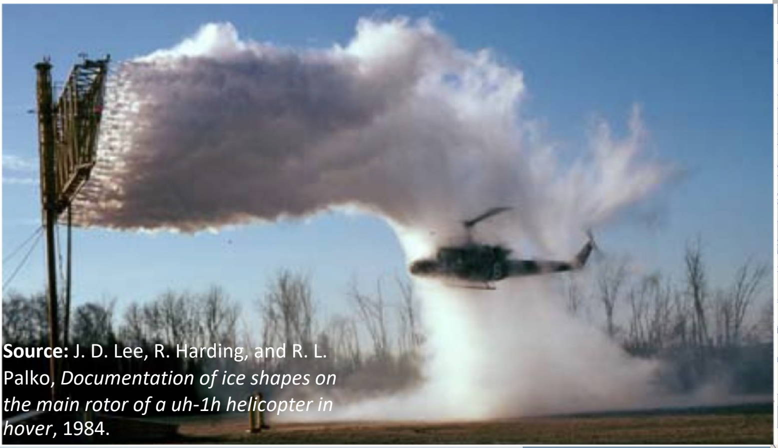
[8] Lebrun, F. "NICETRIP test-ERICA 1/5th scale powered model in the test section no. 2-45m2 of S1MA wind tunnel." *Test Report Number PV* 1 (2014): 17648.

SIMULATION



Icing Simulation

- Initial hover test case
  - For flow visualisation
  - replicate in-flight testing
- Moving Mesh
  - rotating blades
  - Rigidly moving
- Particle tracking
  - supercooled water droplets motion
  - Allows for computation of the collection efficiency



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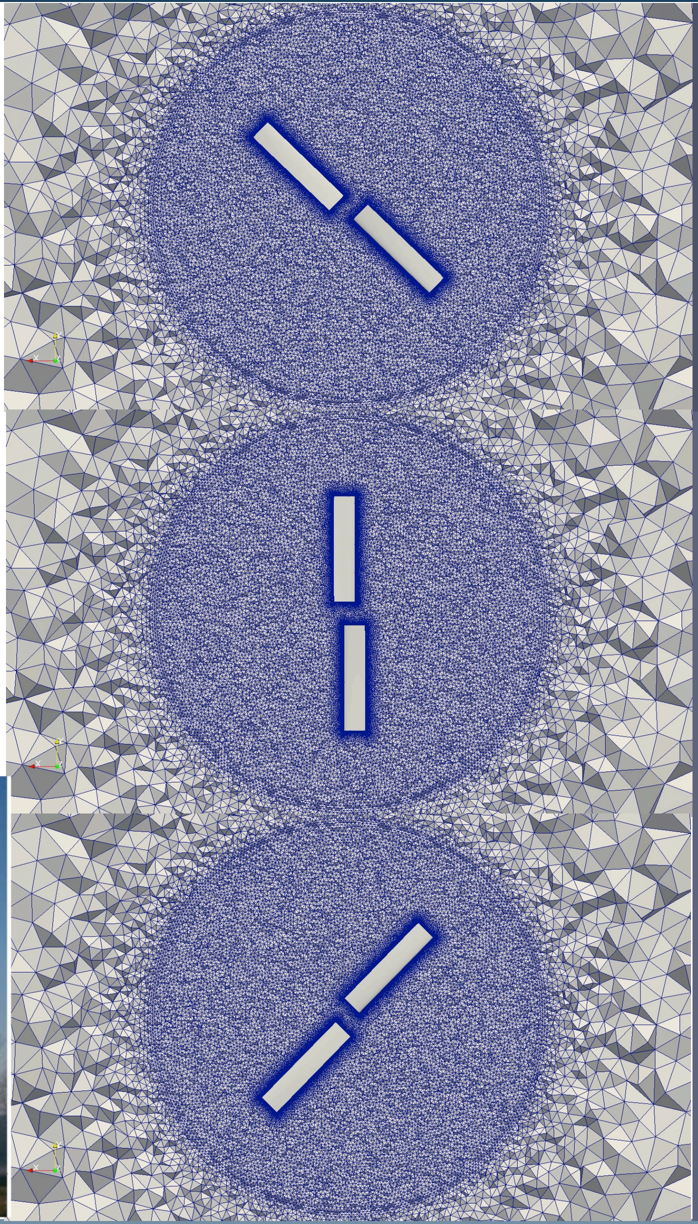
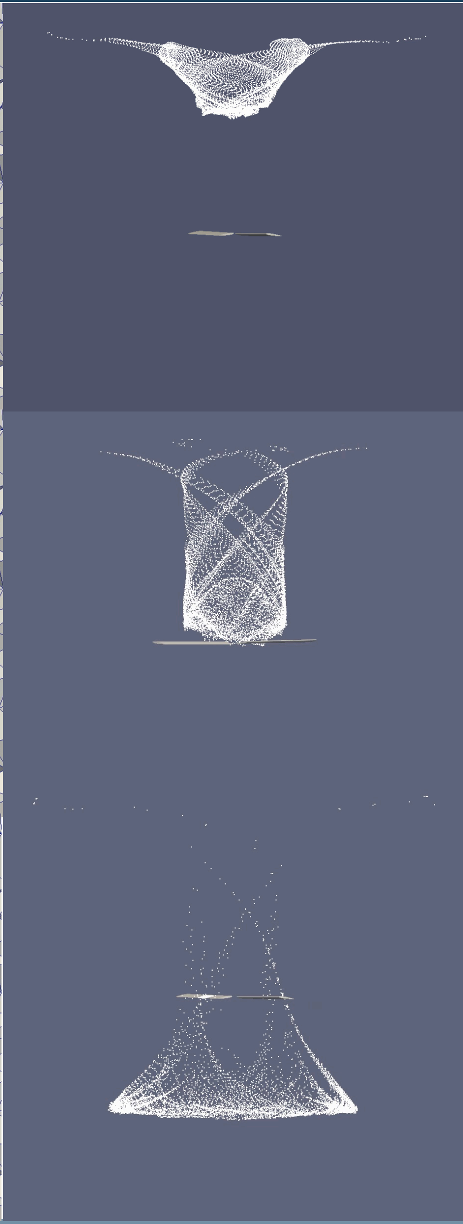




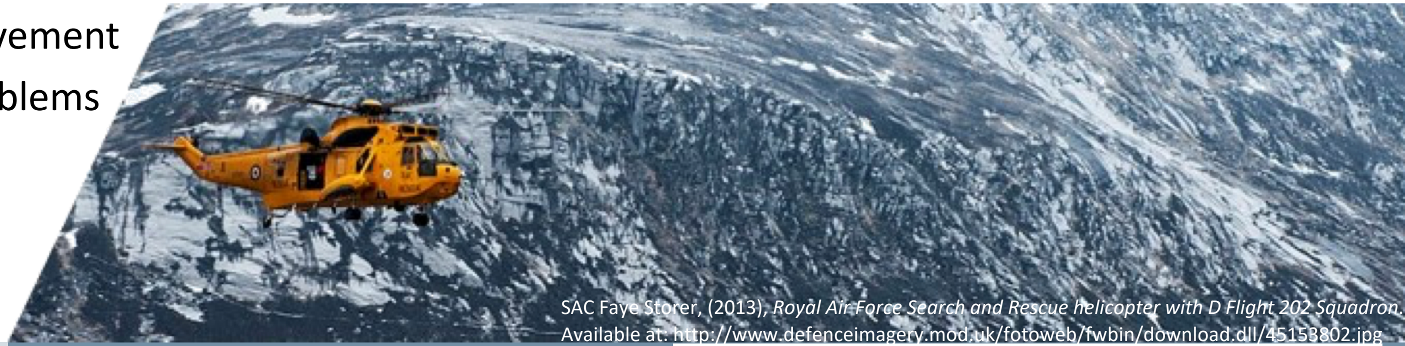
CONCLUSION

- Hover flight condition
  - Experimental
  - Rotating frame
  - Rigid motion

  Good agreement

- Rotor-Fuselage simulations
  - ERICA test will provide a simulation rich in flow physics
  - Periodicity with sliding meshes is still an issue

- Forward flight simulations
  - Development required
  - Blade motion
  - MRF
  - Nested grid movement
  - Multiple FSI problems



SAC Faye Storer, (2013), *Royal Air Force Search and Rescue helicopter with D Flight 202 Squadron.*
Available at: http://www.defenceimagery.mod.uk/fotoweb/fwbin/download.dll/45153802.jpg

SU2

The Open-Source CFD Code

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