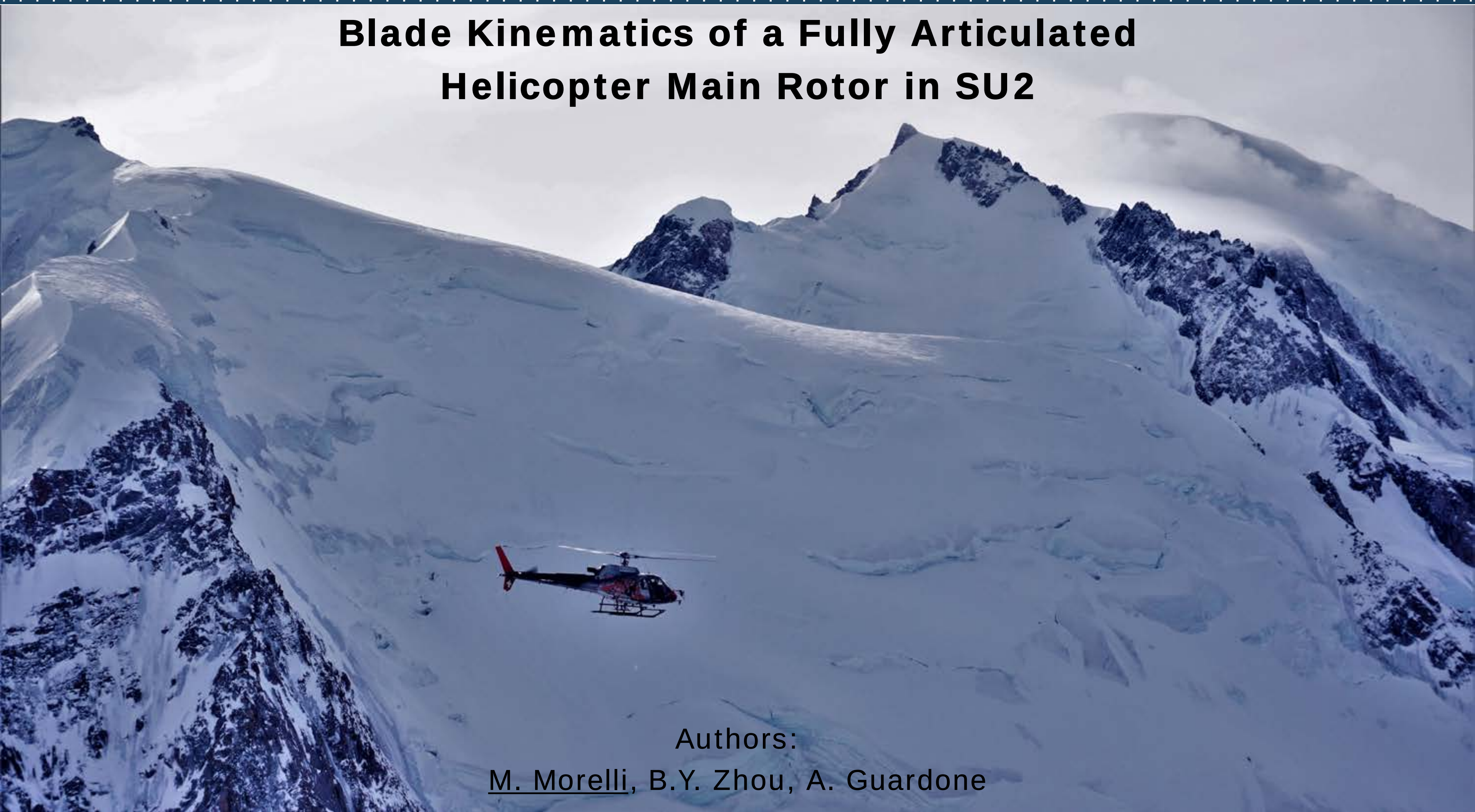
POLITECNICO
MILANO 1863

Blade Kinematics of a Fully Articulated Helicopter Main Rotor in SU2



Authors:
M. Morelli, B.Y. Zhou, A. Guardone

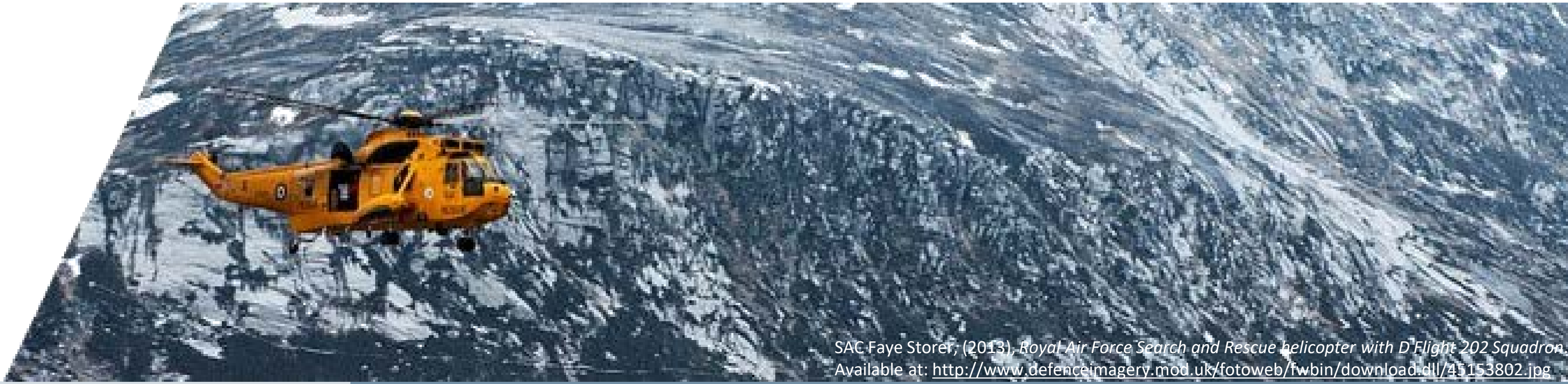
OUTLINE

1. **Part – I**
   - Modelling Helicopters in Forward Flight
   - Implementation within SU2
2. **Part – II**
   - Numerical Results of Icing Simulations

Rotorcraft Icing Environment

- Severely damaging consequences and a threat to flight safety
- Icing on the main rotor alters the blade geometry

Source: BBC NEWS, Mar 2nd 2006



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

Current Research Methods

- Certification for icing demanding/expensive
- FIPS Part 29-C EASA/FAA
- Rigorous testing of main/tail rotors
- Data for certification can come from many sources: in-flight or experimental

Source: NASA, https://www1.grc.nasa.gov/aeronautics/icing/rotorcraft-

Source: NASA, https://www1.grc.nasa.gov/aeronautics/icing/rotorcraft-icing/

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.

Modelling Forward Flight

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

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

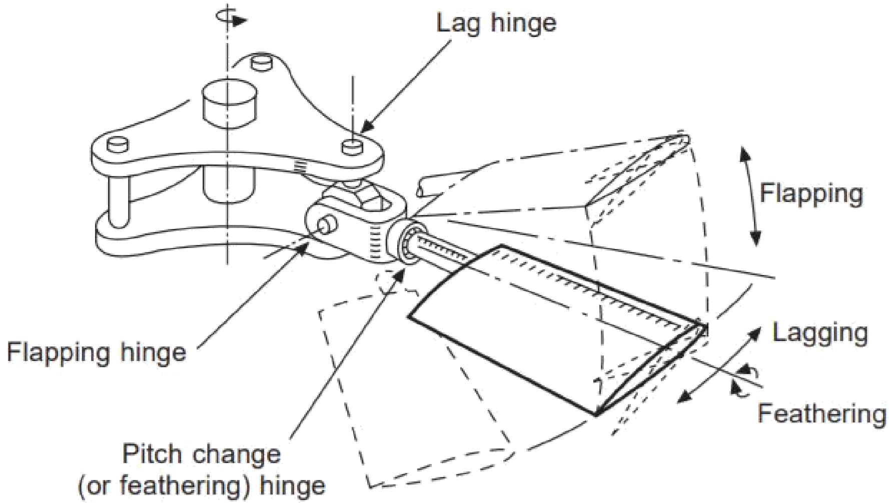
- The differences in the blade normal velocities combined with the requirement that the rotor does not produce pitching or rolling moments is the main challenge.

- Flapping hinge introduced eliminating the rolling moment which arises in forward flight. 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.

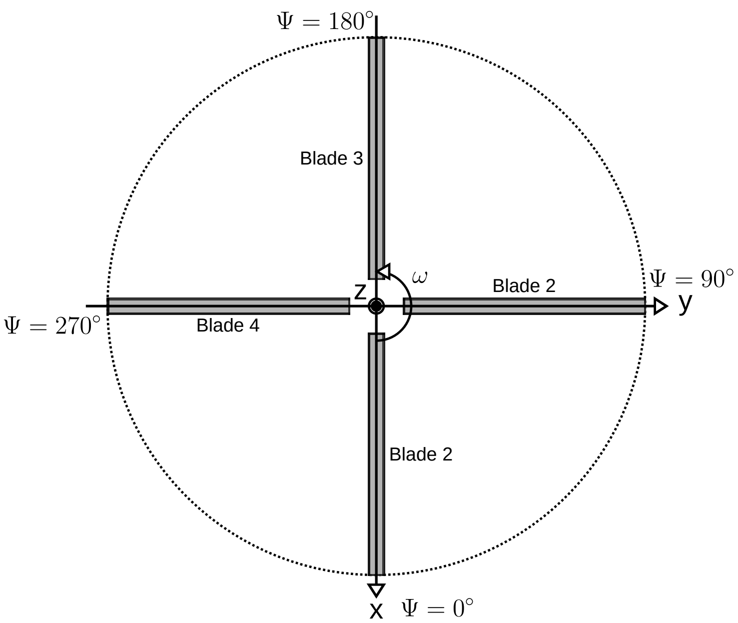
MODELLING FORWARD FLIGHT

- Helicopters in level forward flight involves the following unknowns:
  - Collective pitch
  - Cyclic pitch
  - Flapping and lead-lag harmonics

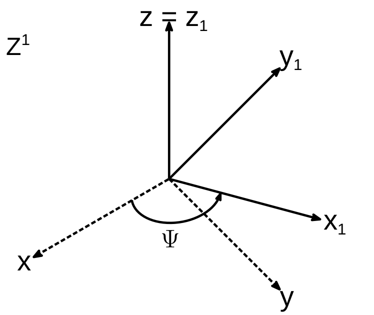
$$\psi = \omega t$$
$$\beta(\psi) = \beta_0 - \beta_{1s}\sin(\psi) - \beta_{1c}\cos(\psi) - \beta_{2s}\sin(2\psi) - \beta_{2c}\cos(2\psi) - ...$$
$$\delta(\psi) = \delta_0 - \delta_{1s}\sin(\psi) - \delta_{1c}\cos(\psi) - \delta_{2s}\sin(2\psi) - \delta_{2c}\cos(2\psi) - ...$$
$$\theta(\psi) = \theta_0 - \theta_{1s}\sin(\psi) - \theta_{1c}\cos(\psi) - \theta_{2s}\sin(2\psi) - \theta_{2c}\cos(2\psi) - ...$$



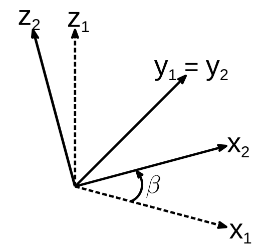
Rotation Around Z-Axes



Rotation - Z^1

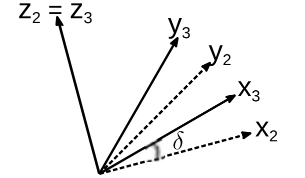


Flapping - Y^2

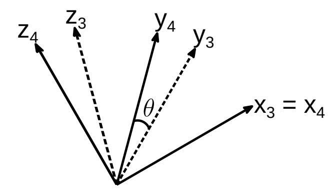


Rotation Matrix Z^1-Y^2-Z^3-X^4

Lead-lag - Z^3



Pitching - X^4



Modelling Forward Flight

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

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

Volumetric movement for rotation

$$C_{\text{rot}} = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Surface movement for blade kinematics

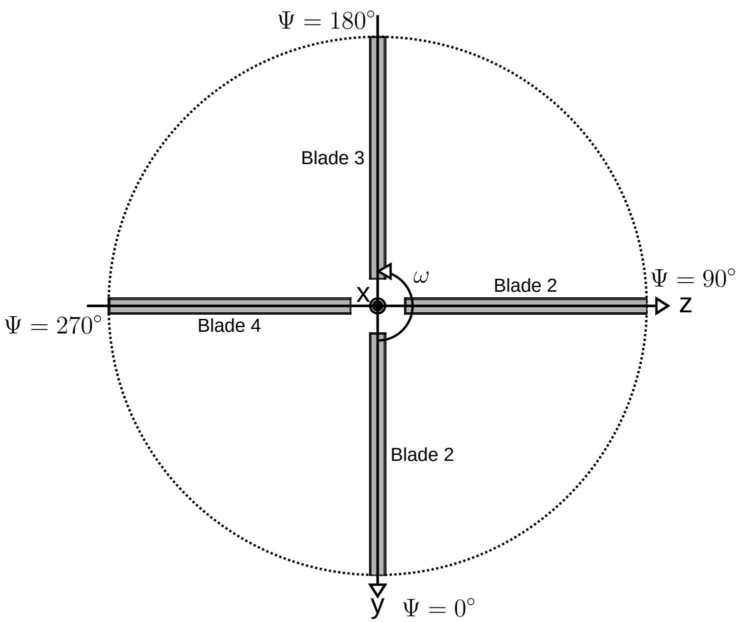
$$C_{\text{flap-leadlag-pitch}} = \begin{pmatrix} \cos\beta\cos\delta & \sin\beta\sin\theta - \cos\beta\cos\theta\sin\delta & \cos\theta\sin\beta + \cos\beta\sin\delta\sin\theta \\ \sin\delta & \cos\delta\cos\theta & -\cos\delta\sin\theta \\ -\cos\delta\sin\beta & \cos\beta\sin\theta + \cos\theta\sin\beta\sin\delta & \cos\beta\cos\theta - \sin\beta\sin\delta\sin\theta \end{pmatrix}$$

Modelling Forward Flight

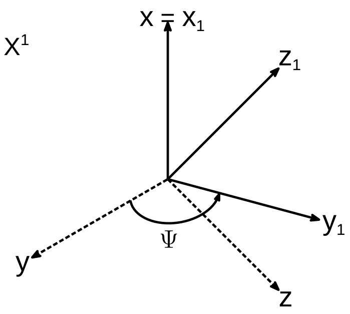
iteration_structure.cpp

```
CIteration::~CIteration(void) { }

void CIteration::SetGrid_Movement(CGeometry ****geometry_container,
          CSurfaceMovement **surface_movement,
          CVolumetricMovement ***grid_movement,
          CFreeFormDefBox ***FFDBox,
          CSolver *****solver_container,
          CConfig **config_container,
          unsigned short val_iZone,
          unsigned short val_iInst,
          unsigned long IntIter,
          unsigned long ExtIter)   {

  case ROTORCRAFT:
      if (rank == MASTER_NODE){
          cout << "Updating grid into hub reference system." << endl;
          grid_movement[val_iZone][val_iInst]->Blade_Rotation(geometry_container[val_iZone][val_iInst][MESH_0],
                                                     config_container[val_iZone], val_iZone, ExtIter);

          cout << "Updating blade surfaces into blade reference systems. " << endl;
          surface_movement[val_iZone]->Blade_Kinematics(geometry_container[val_iZone][val_iInst][MESH_0],
                                               config_container[val_iZone], ExtIter, val_iZone);

          cout << "Deforming the volume grid. " << endl;
          grid_movement[val_iZone][val_iInst]->SetVolume_Deformation(geometry_container[val_iZone][val_iInst][MESH_0],
                                                            config_container[val_iZone], true);

          grid_movement[val_iZone][val_iInst]->UpdateMultiGrid(geometry_container[val_iZone][val_iInst], config_container[val_iZone]);
      }

      break;
}
```

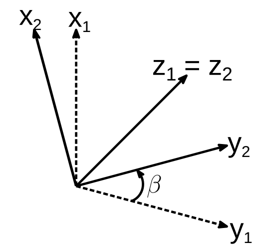
Rotation Around X-Axes



Rotation - X^1

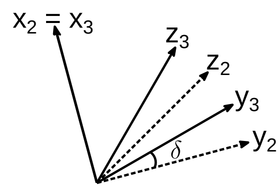


Flapping - Z^2

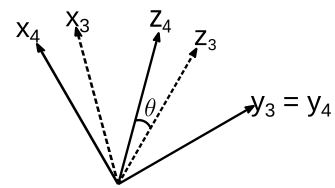


Rotation Matrix X^1-Z^2-X^3-Y^4

Lead-lag - X^3

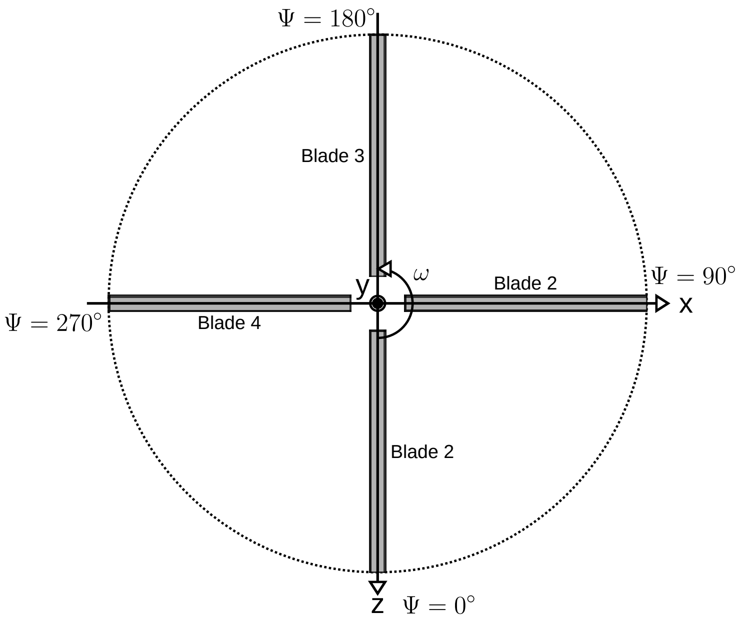


Pitching - Y^4

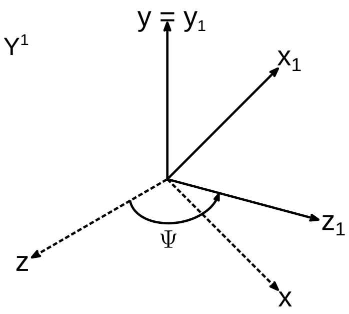


MODELLING FORWARD FLIGHT

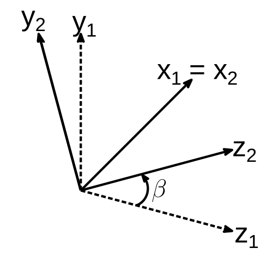
Rotation Around Y-Axes



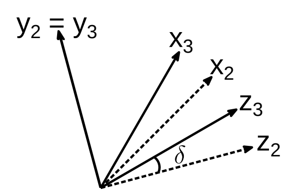
Rotation - Y^1



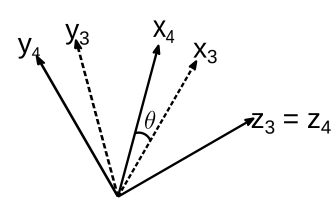
Flapping - X^2



Lead-lag - Y^3

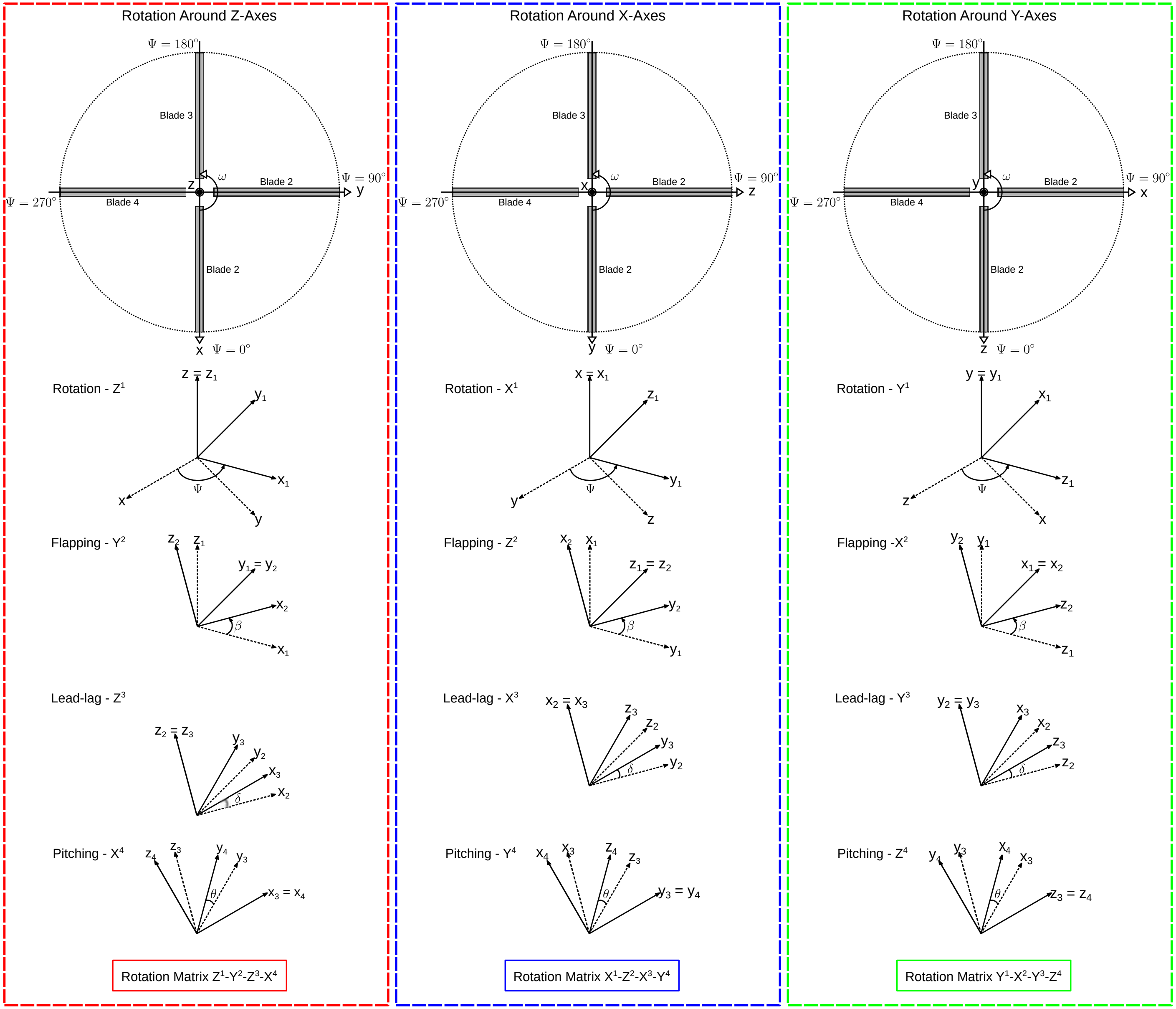


Pitching - Z^4

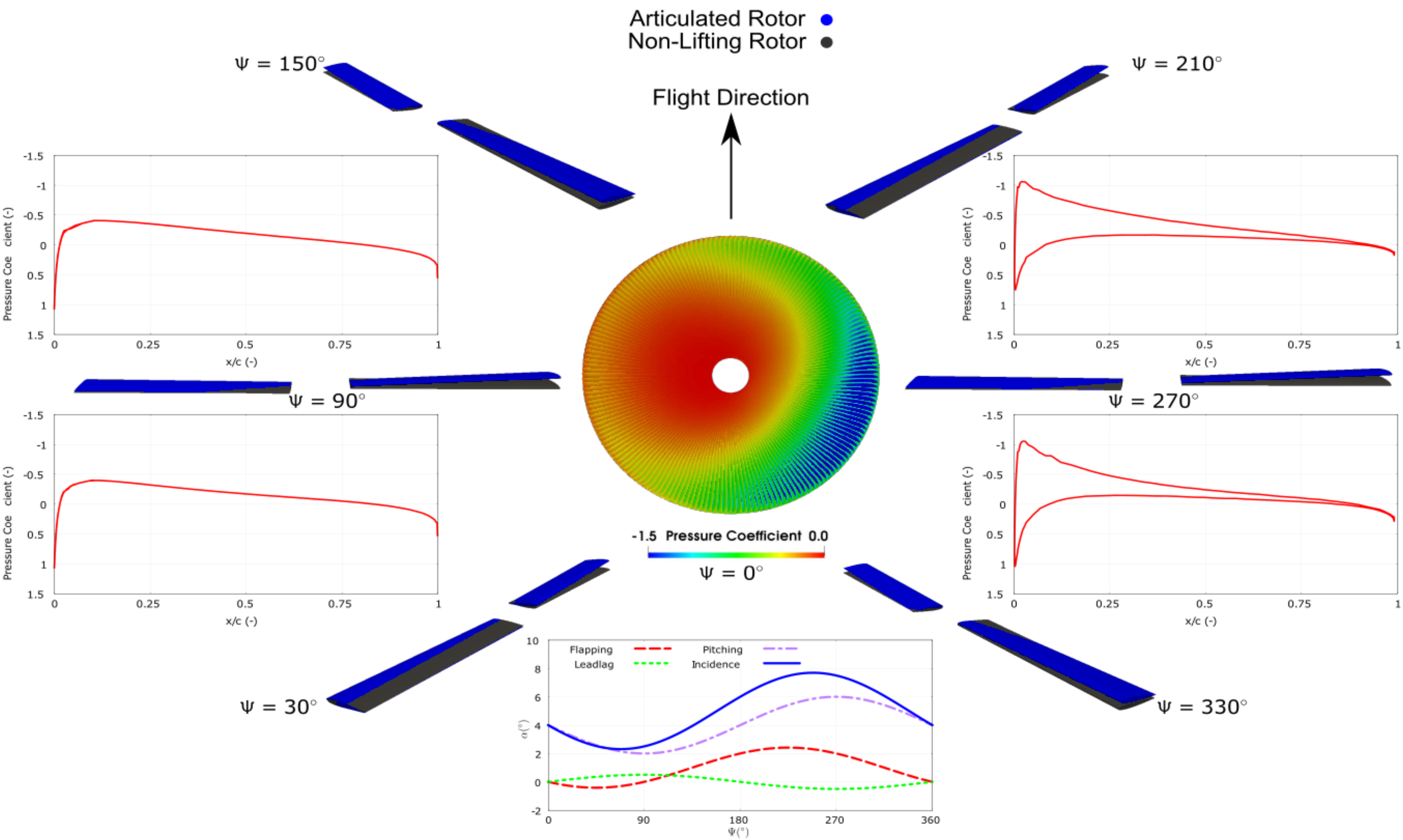


Rotation Matrix Y^1-X^2-Y^3-Z^4

Modelling Forward Flight

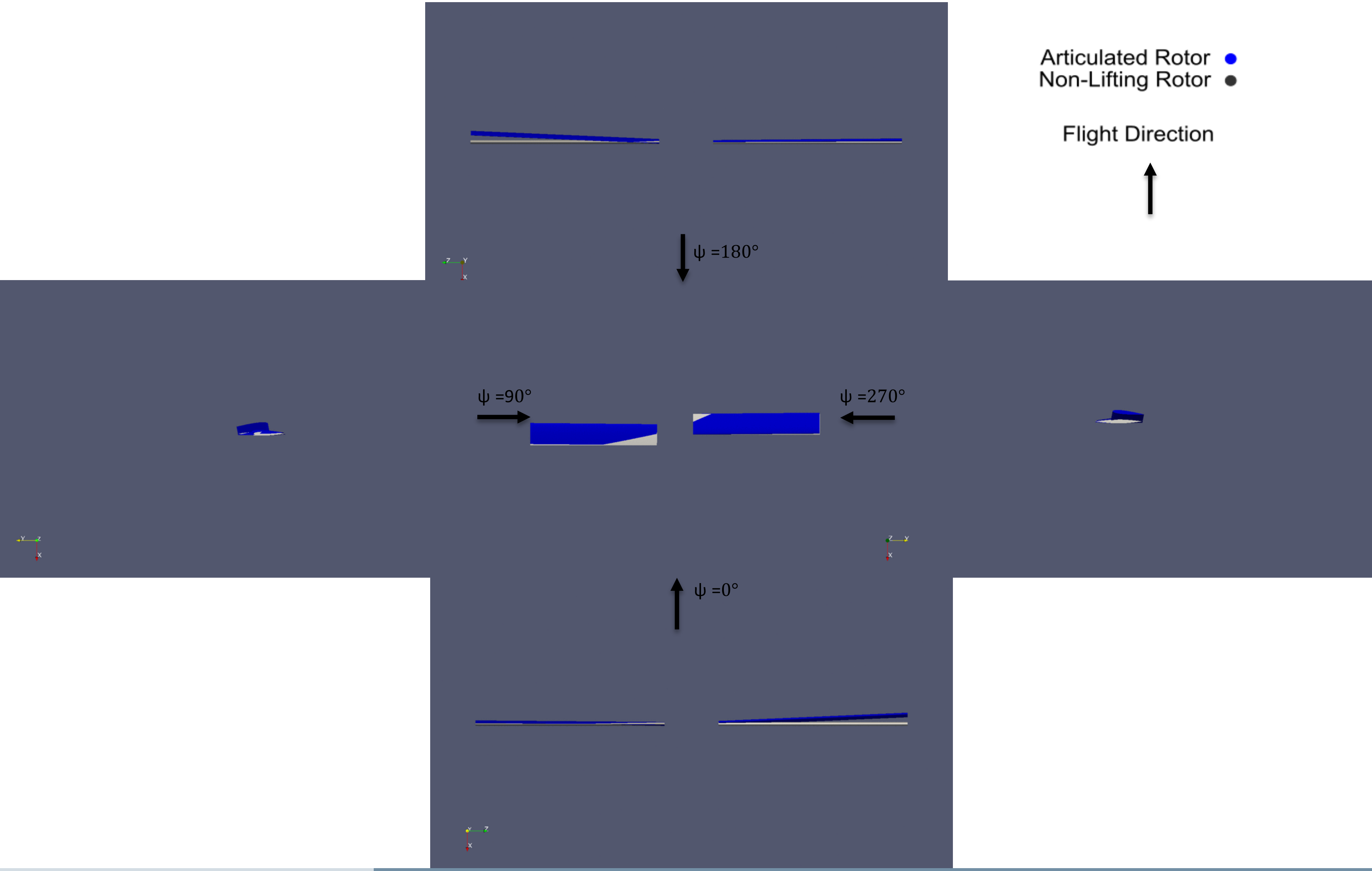


Modelling Forward Flight



Steijl, R., G. Barakos, and K. Badcock. "A framework for CFD analysis of helicopter rotors in hover and forward flight." *International journal for numerical methods in fluids* 51.8 (2006): 819-847.

MODELLING FORWARD FLIGHT



CONFIGURATION FILE

```
% ---------------------- DYNAMIC MESH DEFINITION ----------------------------%
%
% Dynamic mesh simulation (NO, YES)
GRID_MOVEMENT= YES
%
% Type of mesh motion (NONE, FLUTTER, RIGID_MOTION, FLUID_STRUCTURE,
% ROTORCRAFT)
GRID_MOVEMENT_KIND= ROTORCRAFT
%
% Definition of coordinate system. Defined by which axis the rotation occurs on
% (X_AXIS, Y_AXIS, Z_AXIS)
COORD_SYS= Z_AXIS
%
% Angular velocity vector (rad/s) about the hub origin
BLADE_ROTATION_RATE_X= 0.0
BLADE_ROTATION_RATE_Y= 0.0
BLADE_ROTATION_RATE_Z= 180.0
%
% Coordinates of the hub origin
HUB_ORIGIN_X= 0.0
HUB_ORIGIN_Y= 0.0
HUB_ORIGIN_Z= 0.0
%
% Coordinates of the first hinge origin
HINGE_ORIGIN_X= 0.0
HINGE_ORIGIN_Y= 0.0
HINGE_ORIGIN_Z= 0.0
%
% Blade phase offset (degrees) about the azimuth angle
% e.g. A four-bladed rotor (0 90 180 270)
BLADE_PHASE_X= 0.0 0.0
BLADE_PHASE_Y= 0.0 0.0
BLADE_PHASE_Z= 90.0 270.0
%
% Coefficients of the equations of the blades pitching motion and higher harmonics
% Format -> theta(psi) = theta_0 - theta_1s sin(psi) - theta_1c cos(psi) ...
BLADE_PITCH_MOTION= 4.0 2.0 0.0
%
% Coefficients of the equations of the blades flapping motion and higher harmonics
% Format -> beta(psi) = beta_0 - beta_1s sin(psi) - beta_1c cos(psi) ...
BLADE_FLAP_MOTION= 2.0 2.0 2.0
%
% Coefficients of the equations of the blades lead-lag motion and higher harmonics
% Format -> delta(psi) = delta_0 - delta_1s sin(psi) - delta_1c cos(psi) ...
BLADE_LEADLAG_MOTION= 0.0 -2.0 0.0
%
% Moving wall boundary marker(s) (NONE = no marker, ignored for RIGID_MOTION)
MARKER_MOVING=( blade_1, blade_2 )
```

Rotorcraft Icing Analysis

2010 → 2015 → 2016 → Present

- A joint venture in 2010 between the US Government and industry set out to enhance understanding of rotorcraft icing with the development and validation of high-fidelity icing analysis tools

- Two main experimental initiatives were outlined:
    1. A high-quality oscillating airfoil test [1]
    2. A spinning rotor test [2]

- These experimental tests were then the basis for validation of high-fidelity computational rotorcraft icing tools

Bell Helicopter A Textron Company · BOEING · Georgia Tech · SIKORSKY A LOCKHEED MARTIN COMPANY · NASA

[1] Reinert, T., Flemming, R. J., Narducci, R., and Aubert, R. J., "Oscillating Airfoil Icing Tests in the NASA Glenn Research Center Icing Research Tunnel," SAE Technical Paper No. 2011-38-0016., June 2011.
[2] Fortin, G. and Perron, J., "Spinning rotor blade tests in icing wind tunnel," 1st AIAA Atmospheric and Space Environments Conference, June 2009.

NUMERICAL RESULTS

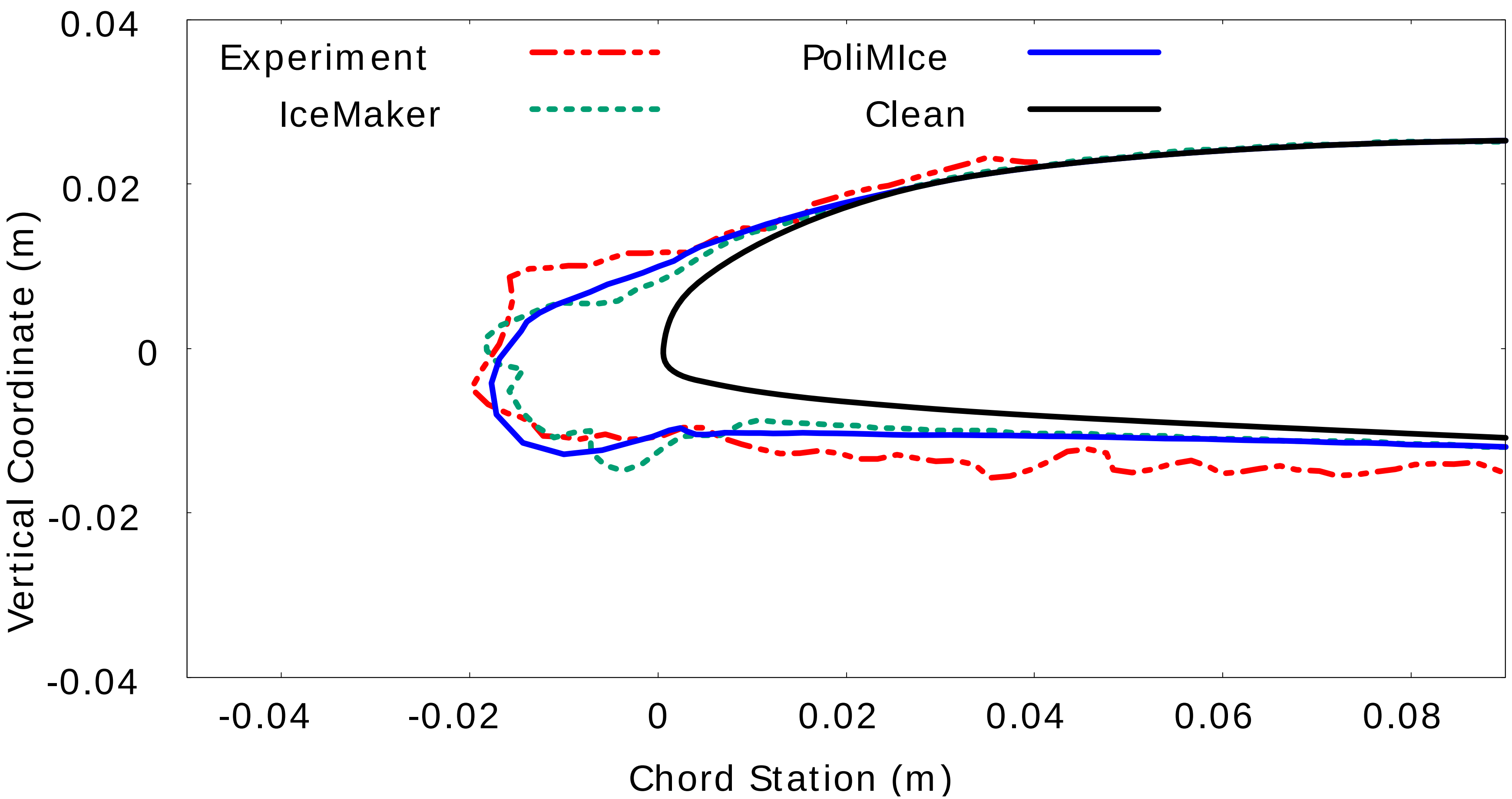
1. Test Case – **Run Number 36**
   – Icing Analysis
   – Performance Analysis
   – Flow Field Analysis
   – Acoustic Analysis

2. Test Case – **Run Number 61**
   – Icing Analysis
   – Performance Analysis
   – Flow Field Analysis
   – Acoustic Analysis

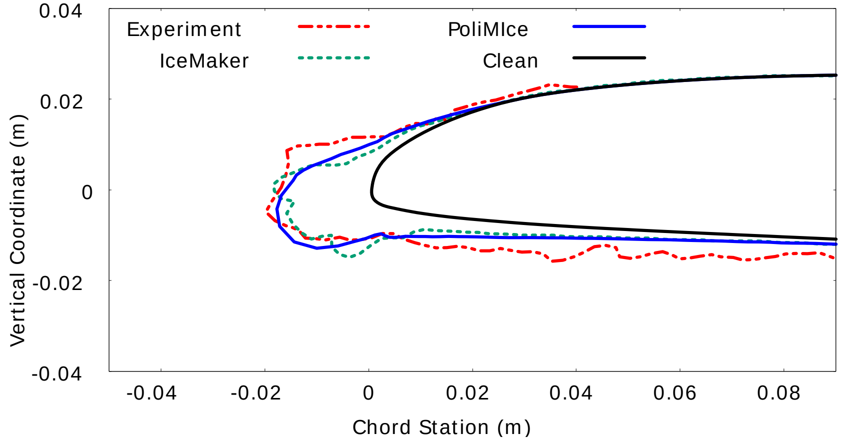
Test Case (number)	Air Speed (m/s)	α (°)	LWC (g/m^3)	Time (seconds)
Run 36	77	5±6	0.5	600
Run 62	77	5±6	0.5	900
Run 61	77	5±6	1.0	600
Run 50	132	5±6	0.5	600
Run 55	132	10±6	0.5	600
Run 57	132	10	0.5	600

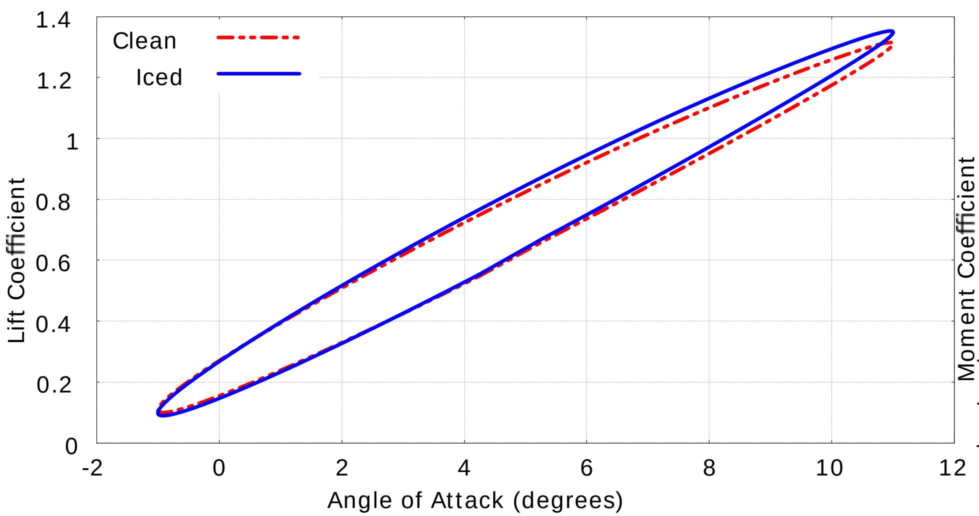
TEST CASE 1 - RUN NUMBER 36

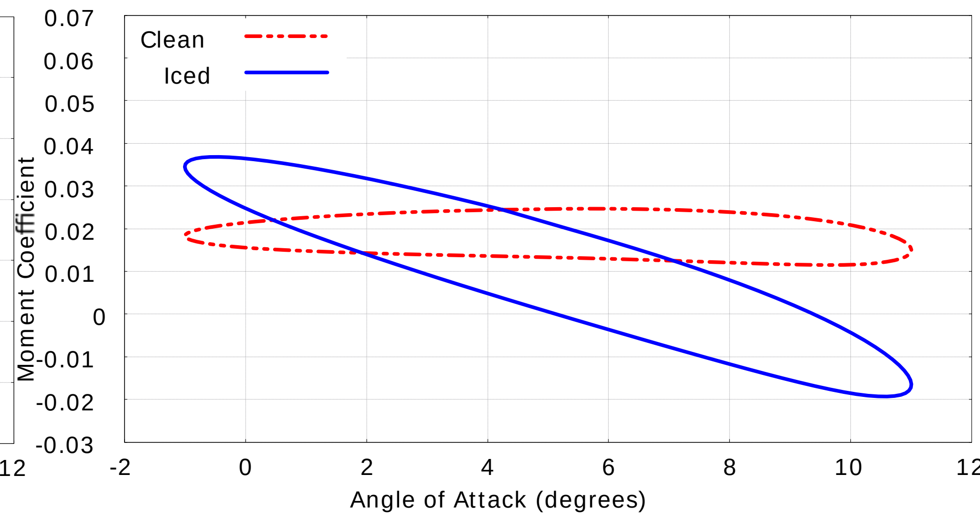
Ice Shape Analysis



Performance Analysis

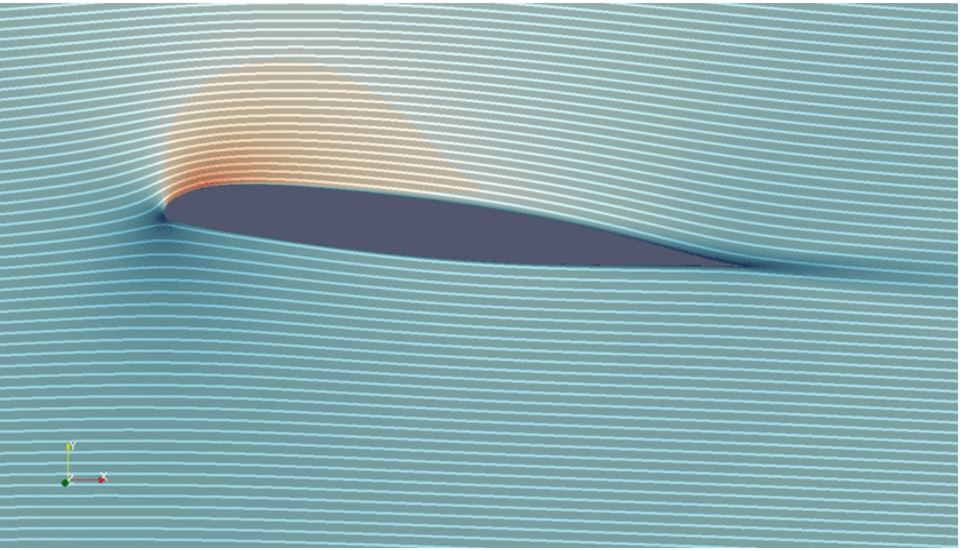




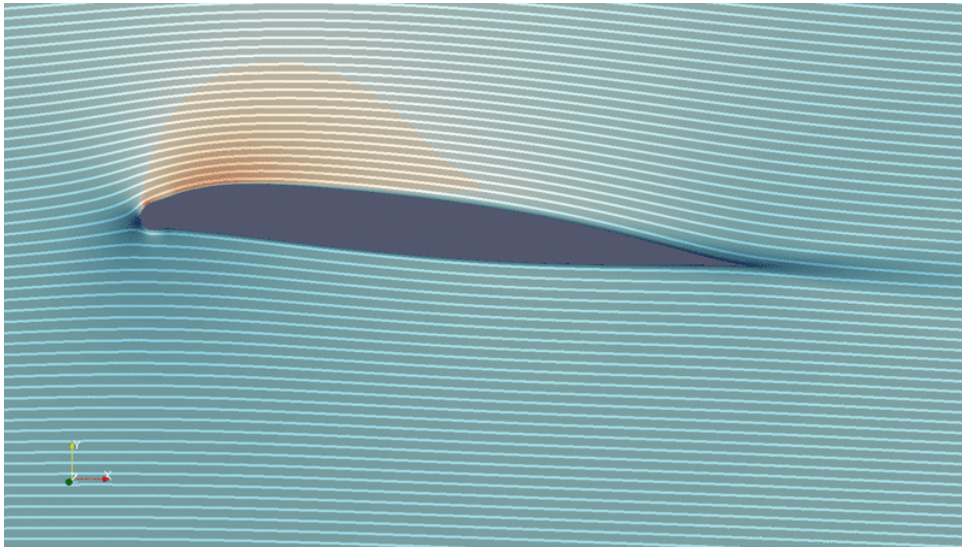


TEST CASE 1 - RUN NUMBER 36

Flow Field Analysis



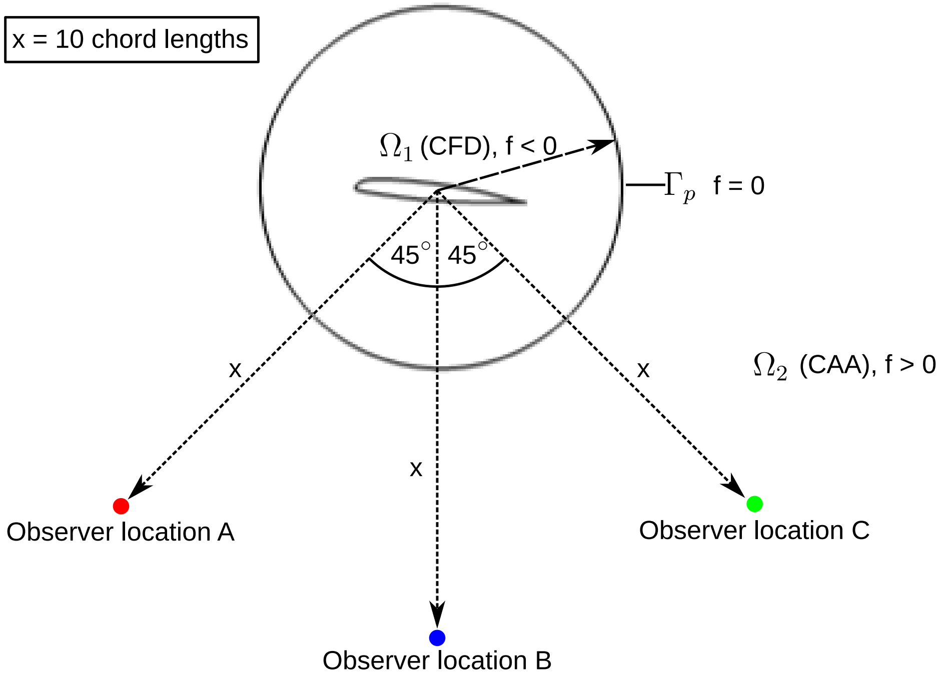
Clean

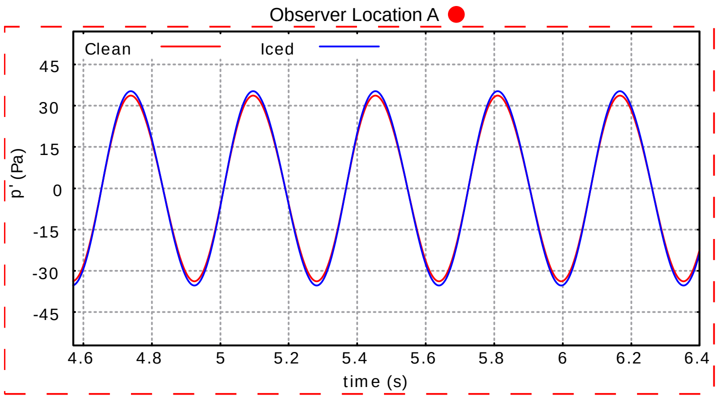


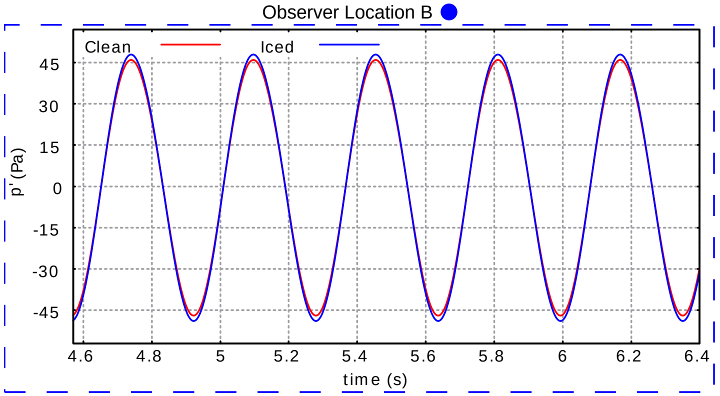
Iced

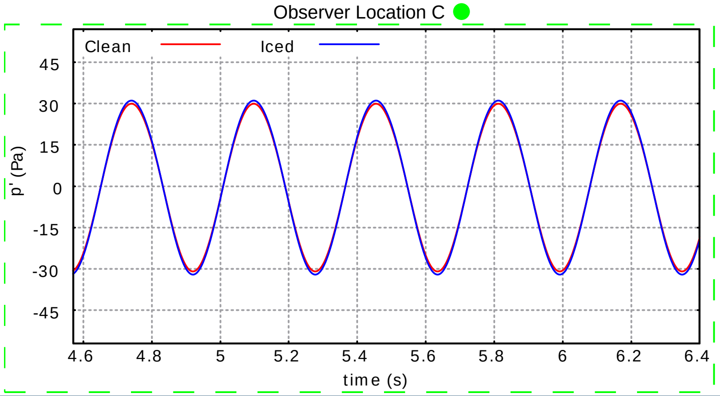
Test Case 1 - Run Number 36

Acoustic Analysis

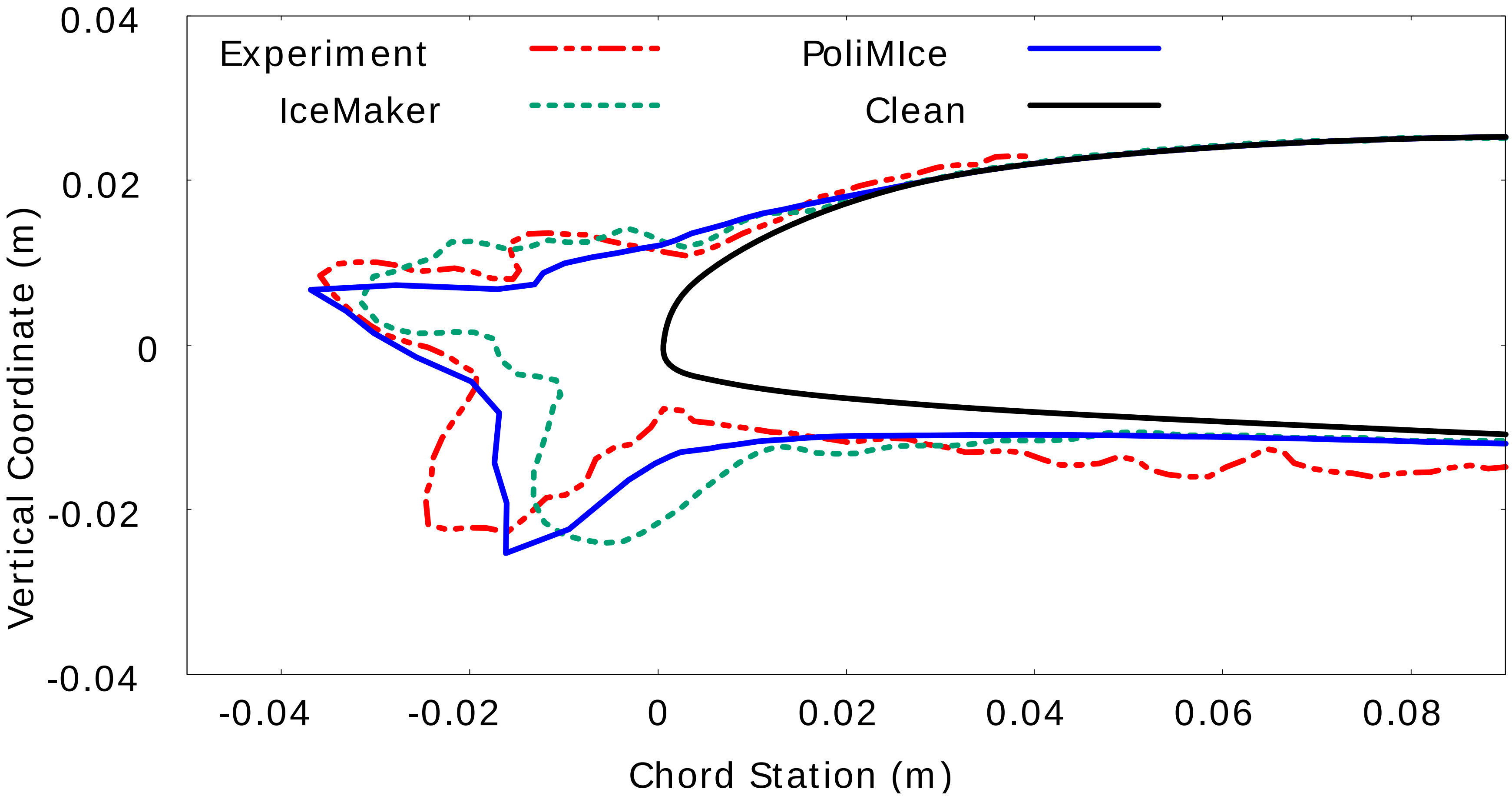






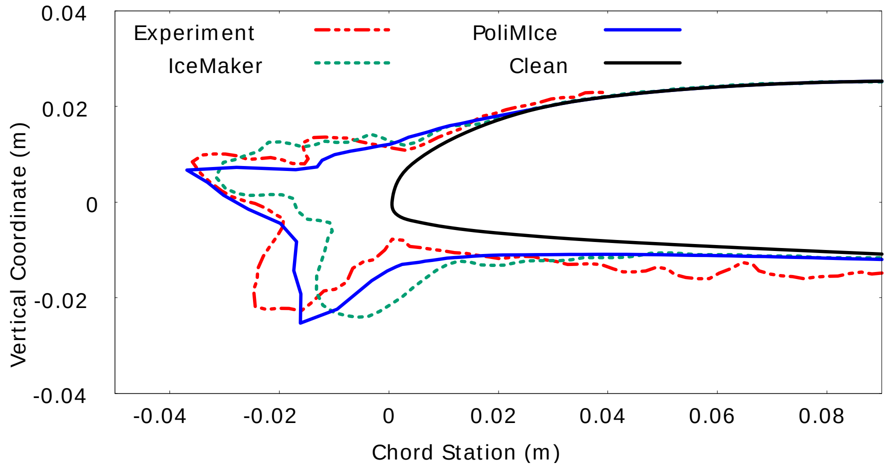


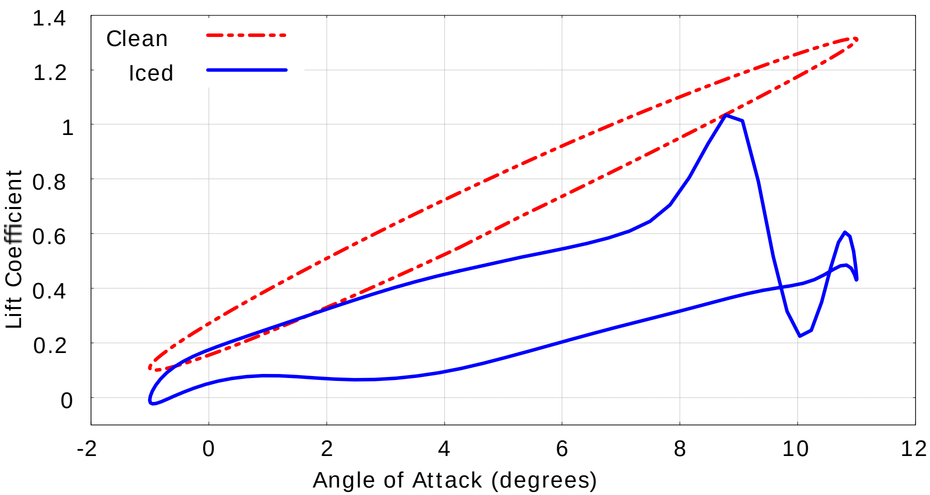
Ice Shape Analysis

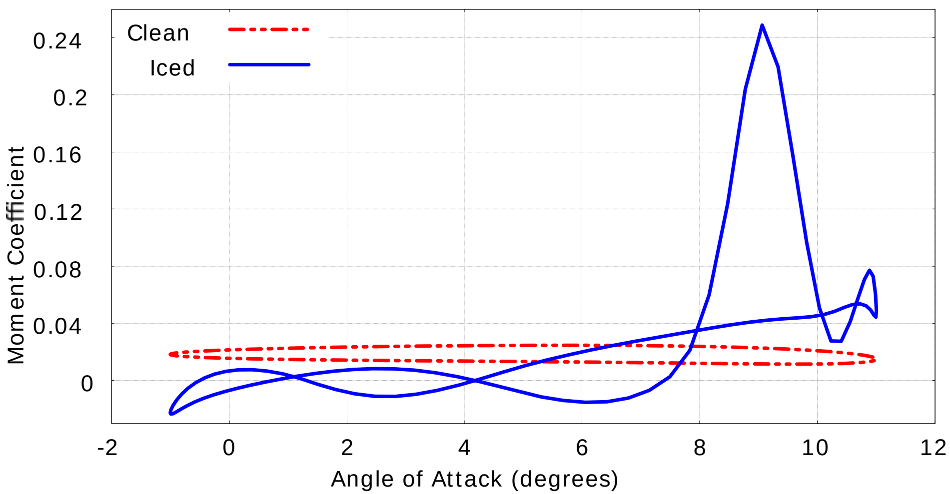


TEST CASE 2 - RUN NUMBER 61

Performance Analysis







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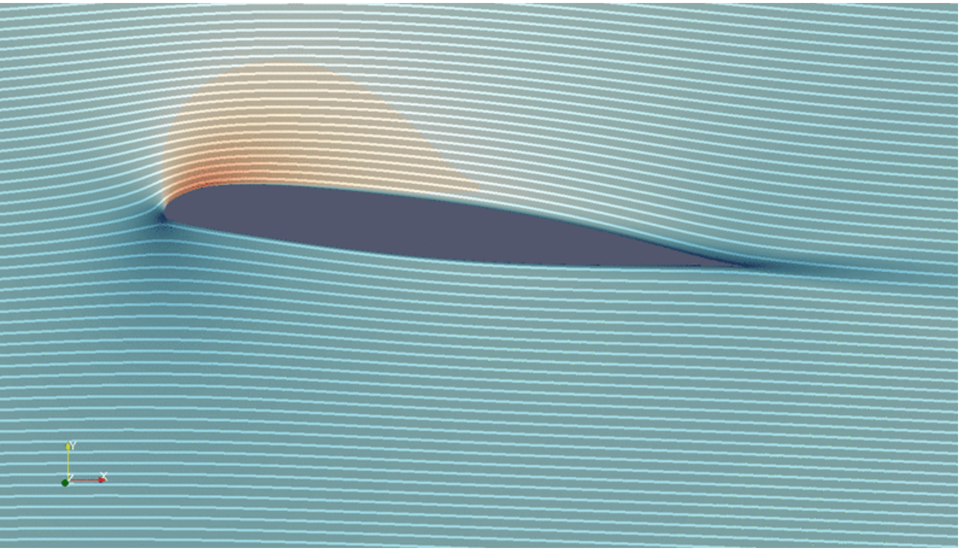
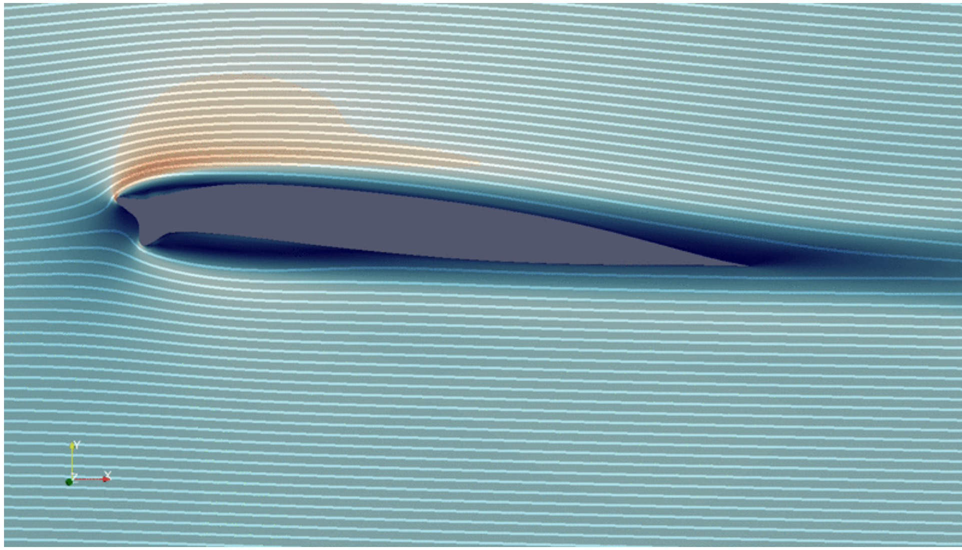
Test Case 1 - Run Number 61

Flow Field Analysis



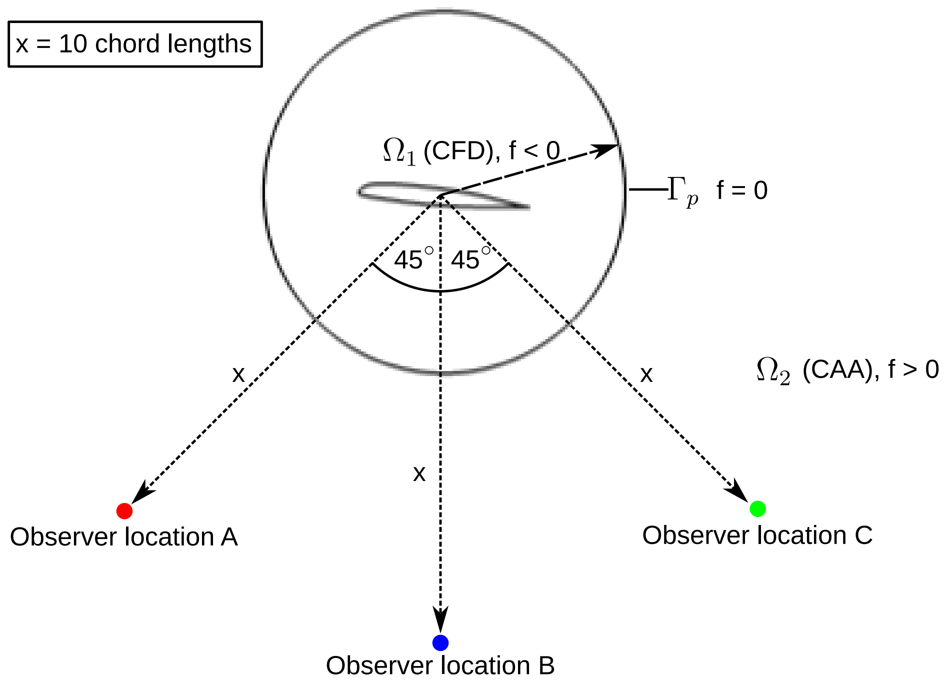
Clean

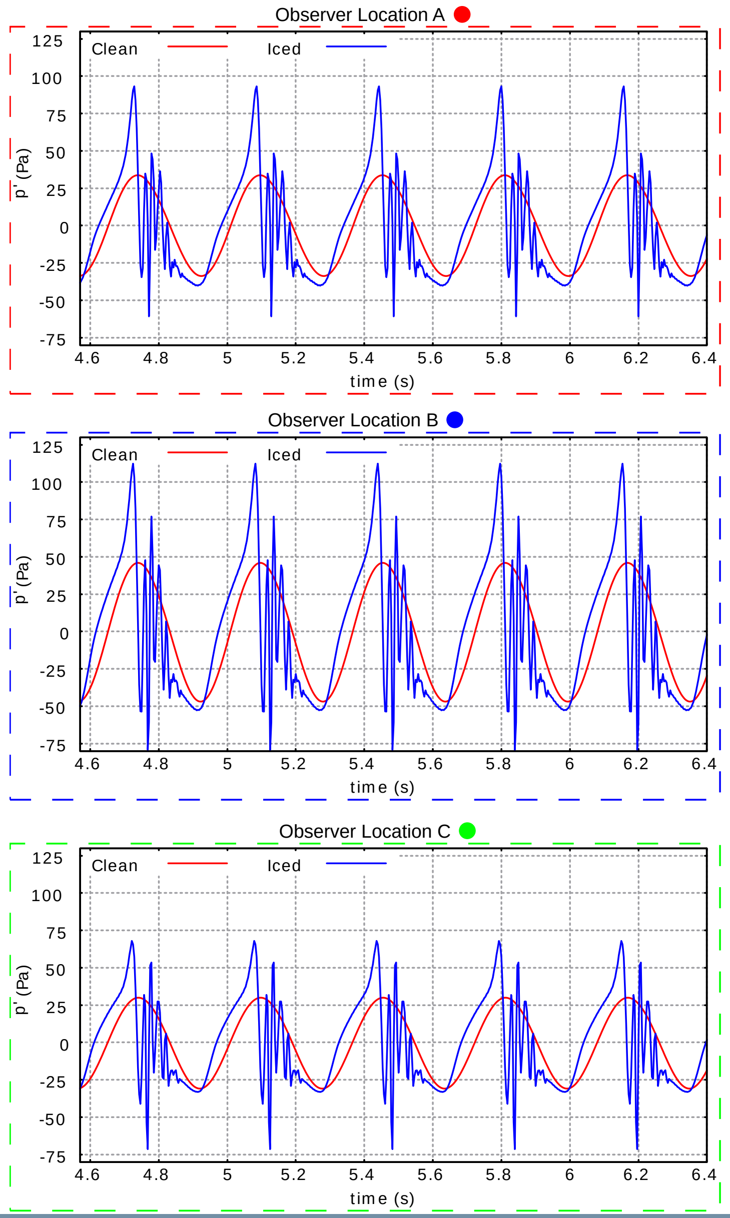


Iced

Test Case 2 - Run Number 61

Acoustic Analysis





CONCLUSION

1. The method for implementing the main rotor blade kinematics within SU2 now allows the possibility of simulating helicopter main rotors in forward flight.

2. The methods supports the multi-zone approach within SU2 so the sliding mesh can be used to simulate complex helicopter fuselage-rotor interactions in forward flight.

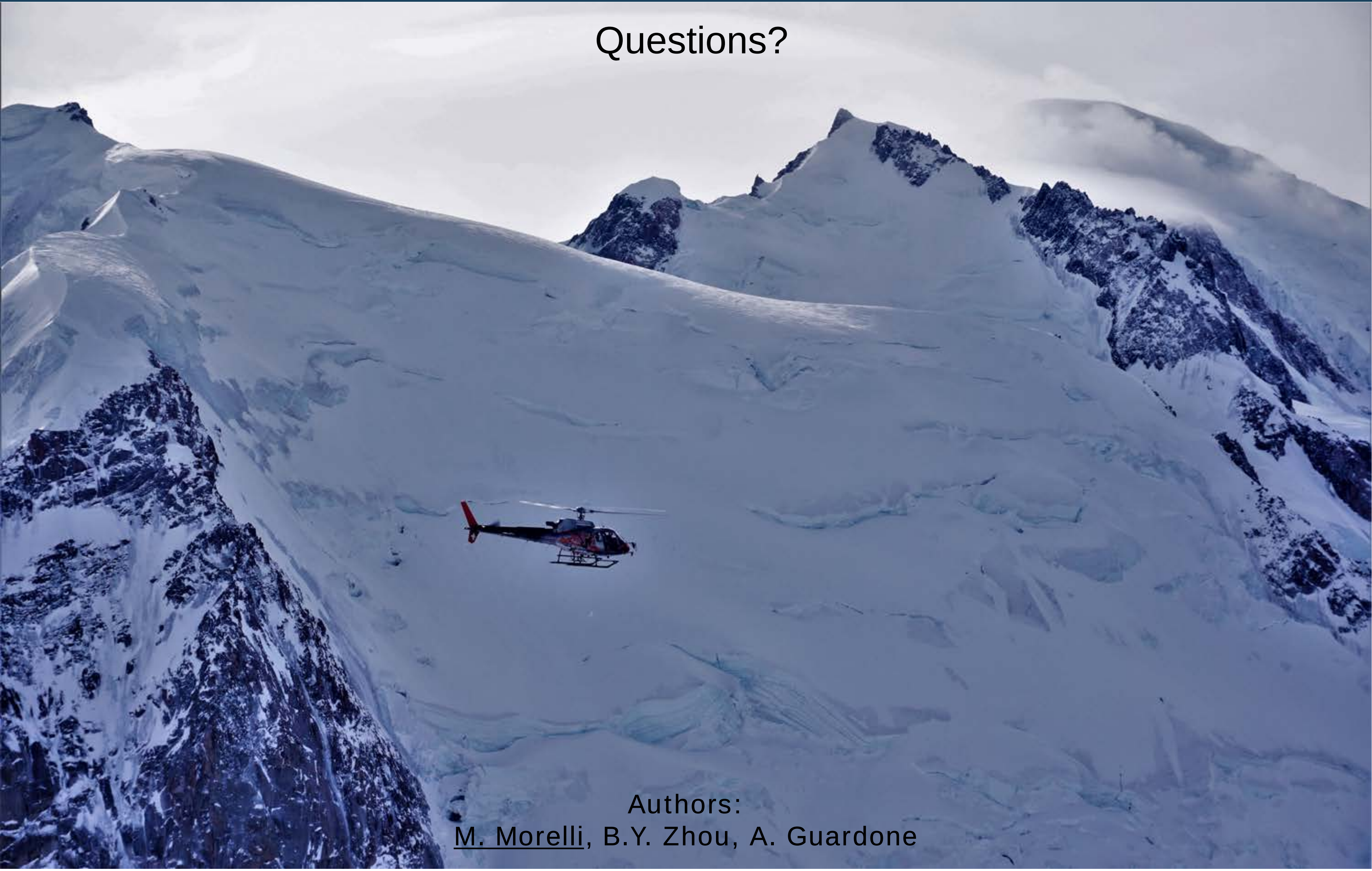
3. The collaboration within the SU2 community allows for excellent multi-disciplinary projects such as the coupling between modelling ice accretion and noise to help develop new technologies such as noise ice detection warning systems

Future Work

- Validate the flow field of the resultant blade kinematics. HART-II experimental test campaign has been selected. This experimental test case will also allow us to assess the acoustics produced from the main rotor in descending flight when strong BVI is present.

- Once at a stage where there is complete verification of the method and validation of the results there will be a pull request to merge the feature_ROTORCRAFT branch into the main release branch.

Thank you for Listening



Questions?

Authors:
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