FAST NON-EMPIRIC ROTOR NOISE PREDICTION MODEL FOR INSTALLED PROPULSORS

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Concept

- Two Steps Approach:
  - Rotor replaced by its unsteady loading and displacement on fluid for Computational Aeroacoustics (CAA)
  - Use RANS with Actuator Disc (AD) model to represent rotor
    - Used as background mean flow
    - AD disc loading as input to CAA rotor model

Non-empiric model

NO rotating grids

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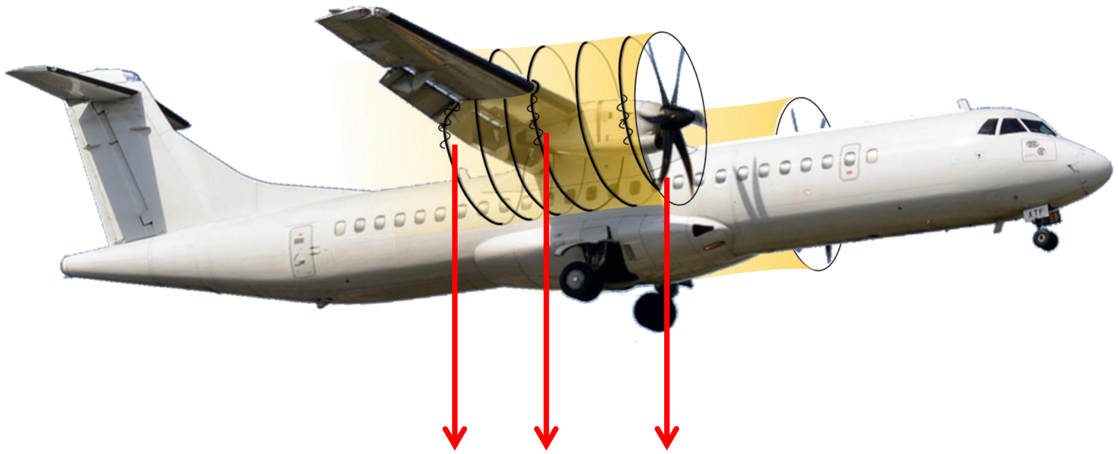

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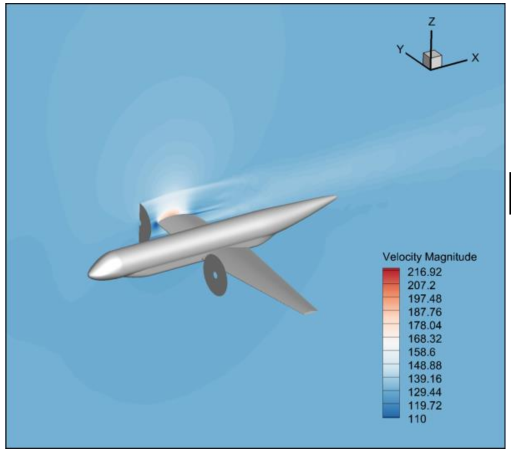
Fast Non-Empiric Prediction Model

RANS AD Solution



LEE

Modelled Rotor Fluid Displacement

Modelled Rotor Loading

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' \mathbf{U_0} + \rho_0 \mathbf{u}') = \dot{\theta}'$$

$$\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u}' \cdot \nabla)\mathbf{U_0} + (\mathbf{U_0} \cdot \nabla)\mathbf{u}' + \frac{\nabla p'}{\rho_0} - \rho' \frac{\nabla p_0}{\rho_0^2} = \frac{\boldsymbol{f}'}{\rho_0}$$

$$\frac{\partial p'}{\partial t} + \mathbf{u}' \cdot \nabla p_0 + \mathbf{U_0} \cdot \nabla p' + \gamma p_0 \nabla \cdot \mathbf{u}' + \gamma p' \nabla \cdot \mathbf{u_0} = \frac{c_0^2}{\gamma} \dot{\theta}'$$

or

APE+VCE

$$\left.\begin{aligned} &\frac{\partial p'}{\partial t} + c_0^2 \nabla \cdot \left(\mathbf{U_0} \frac{p'}{c_0^2} + \rho_0 \mathbf{u}^a \right) = -c_0^2 \nabla \cdot (\rho_0 \mathbf{u}^r) + c_0^2 \dot{\theta}' \\ &\frac{\partial \mathbf{u}^a}{\partial t} + \nabla (\mathbf{U_0} \cdot \mathbf{u}^a) + \nabla \left(\frac{p'}{\rho_0} \right) = \mathbf{0} \end{aligned}\right\} \text{APE}$$

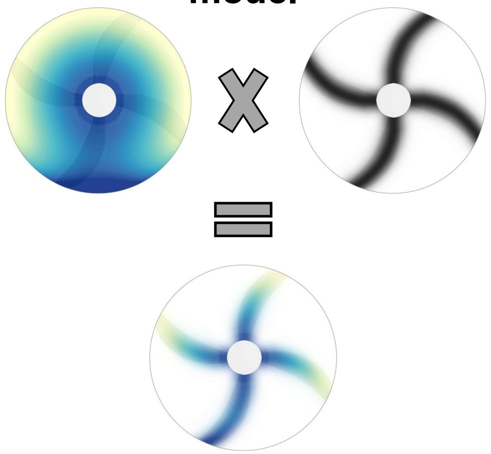
Modelled Rotor Fluid Displacement

$$\left.\frac{\partial (\rho_0 \mathbf{u}^r)}{\partial t} + \nabla \cdot (\rho_0 \mathbf{U_0} \mathbf{u}^r) = \boldsymbol{f}'\right\} \text{VCE}$$

Modelled Rotor Loading

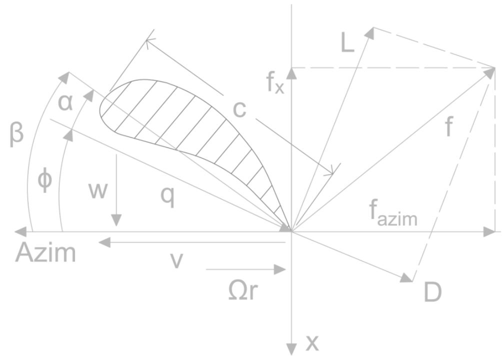
Rotor Noise Source Model

Actuator Disc (AD) based model

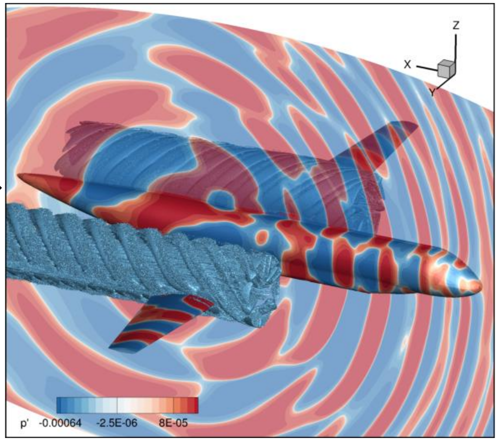


or

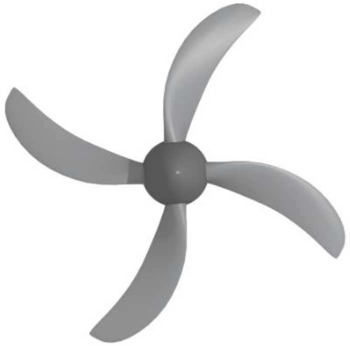
Blade Element Theory (BET) based model



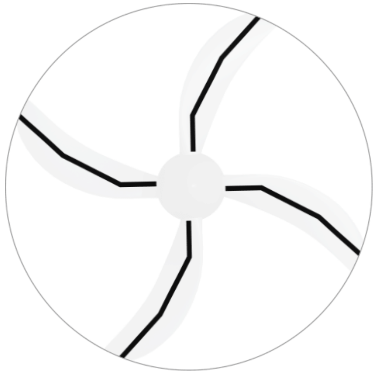
CAA Solution



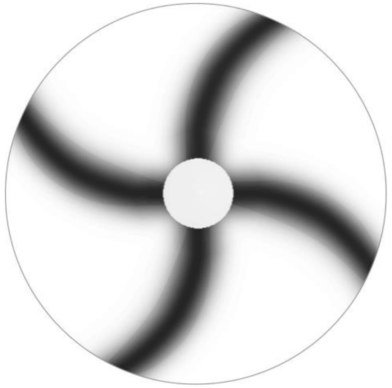
Actuator Disc Based Model, Rotor Loading Source



Original rotor blades to be modeled



Line sources of constant strength $w = 1/N_{Blade}$, defined from the original rotor blades



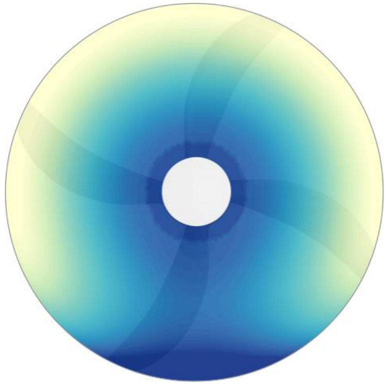
Regularisation of line sources of constant strength w with Gaussian Kernel $K(\mathrm{r}, \phi, \mathrm{x})$

Gaussian Regularized Sources

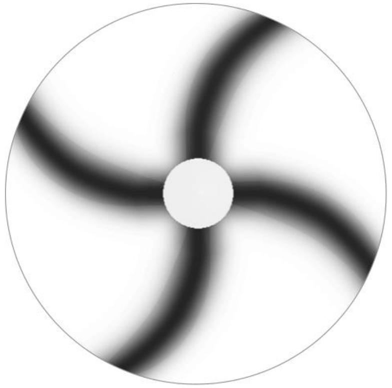
$$\boldsymbol{S}' = \boldsymbol{S} \cdot K(\mathrm{r}, \phi, \mathrm{x}) - \overline{\boldsymbol{S} \cdot K(\mathrm{r}, \phi, \mathrm{x})}$$

$K(\mathrm{r}, \phi, \mathrm{x})$ Gaussian Regularization Kernel

$\boldsymbol{S} = (w, w, w)$ Source Vector



AD surface RANS solution

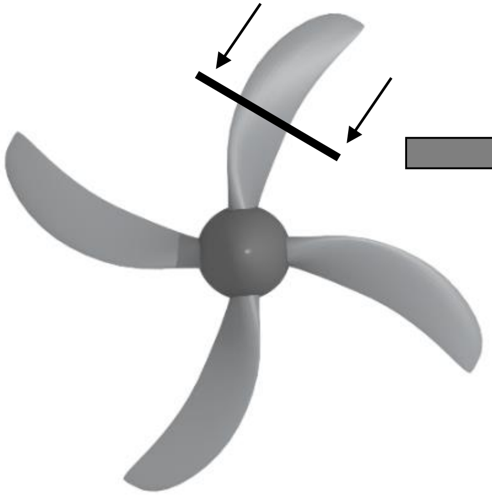


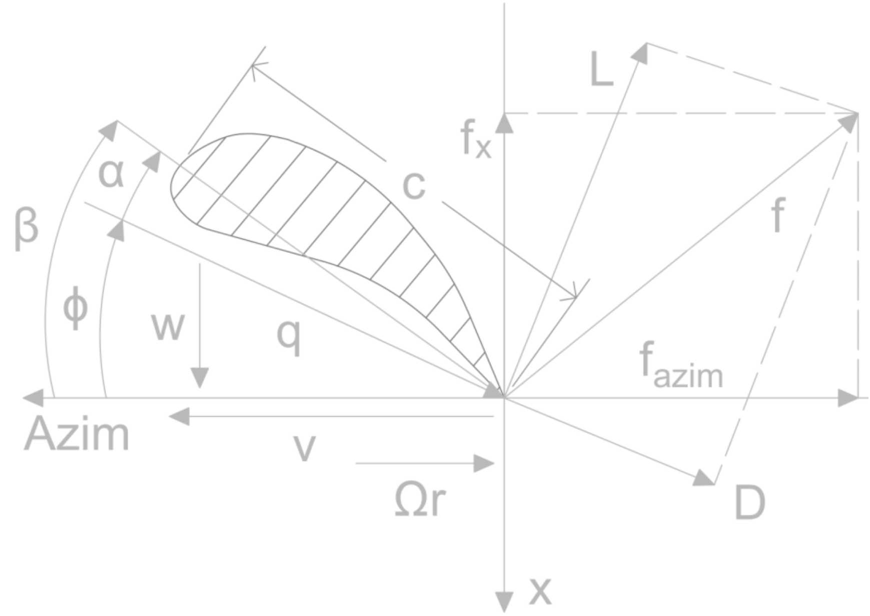
Regularised line sources of constant strength w

Resulting rotor line sources

Blade Element Theory Based Model, Rotor Loading Source

Original rotor blades to be modeled





- L = Lift force
- D = Drag force
- q = Inflow velocity
- α = Angle of attack
- ϕ = Inflow velocity angle
- β = Twist angle
- c = Airfoil chord length
- Ωr = Rotational speed

$$\boxed{\begin{pmatrix} w \\ v \end{pmatrix} = \begin{pmatrix} w_0 \\ v_0 \end{pmatrix} + \begin{pmatrix} w^a + w^r \\ v^a + v^r \end{pmatrix}}$$

- $L = \frac{\rho}{2} q^2 c c_L(\alpha)$
- $D = \frac{\rho}{2} q^2 c c_D(\alpha)$
- $c_L(\alpha), c_D(\alpha), \beta, c$

(Same as AD RANS Input Tables)

$$\boldsymbol{S} = \begin{pmatrix} S_r \\ S_{Azim} \\ S_X \end{pmatrix} = \begin{pmatrix} 0 \\ -f_{Azim} \\ -f_X \end{pmatrix}$$

$$f_{Azim} = -\operatorname{sgn}(\Omega)\left(L sin(\phi) + D cos(\phi)\right)$$

$$f_X = -L cos(\phi) + D sin(\phi)$$

Gaussian Regularized Sources

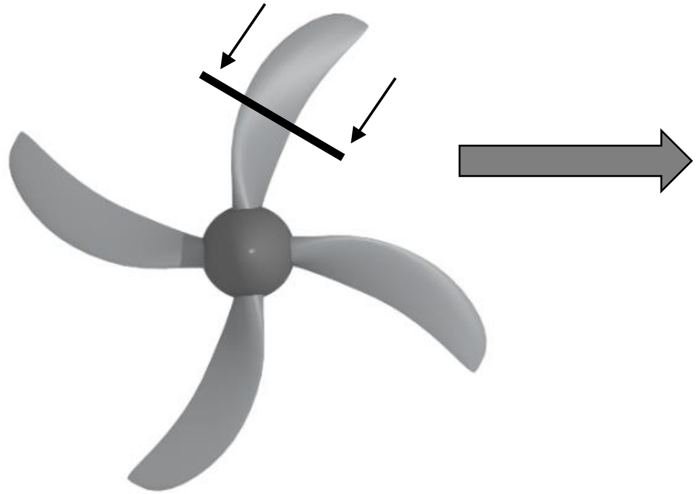
$$\boldsymbol{S}' = \boldsymbol{S} \cdot K(\mathrm{r}, \phi, \mathrm{x}) - \overline{\boldsymbol{S} \cdot K(\mathrm{r}, \phi, \mathrm{x})}$$

$K(\mathrm{r}, \phi, \mathrm{x})$ Gaussian Regularization Kernel

$\boldsymbol{S}((w, v))$ Source Vector

$\overline{\boldsymbol{S}((w_0, v_0))}$ Source Mean Value Vector

Rotor Fluid Displacement Source



$$m(r) = \rho A_{airfoil}(r)$$

$$m_{Regularised}(r) = m(r) \cdot K(\mathrm{r}, \phi, \mathrm{x})$$

- ρ = Air density
- $A_{airfoil}$ = Blade section profile area
- $K(\mathrm{r}, \phi, \mathrm{x})$ = Gaussian regularization kernel

- For AD-based model, $m(r)$ specified on circular surface
- For BET-based model, $m(r)$ specified directly as line source distribution

Assuming constant mass distribution

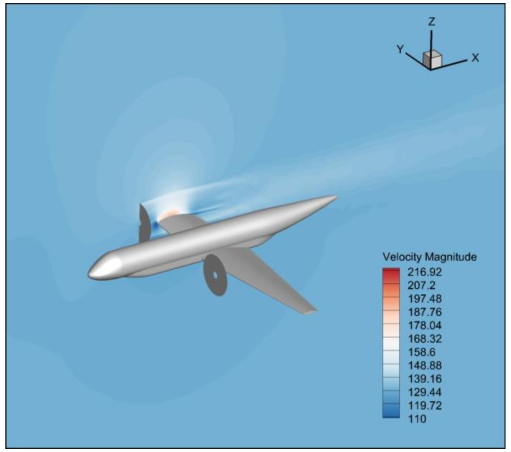
$$\dot{m}_{Regularised}(r) = \frac{\partial\left(m_{Regularised}(r)\right)}{\partial t} = \frac{\partial\left(m(r) \cdot K(\mathrm{r}, \phi, \mathrm{x})\right)}{\partial t} = m(r) \cdot \frac{\partial\left(K(\mathrm{r}, \phi, \mathrm{x})\right)}{\partial t} = m(r) \cdot \frac{\partial\left(K(\mathrm{r}, \phi, \mathrm{x})\right)}{\partial \phi} \frac{\partial \phi}{\partial t}$$

$$\boxed{\dot{m}_{Regularised}(r) = m(r) \cdot \frac{\partial\left(K(\mathrm{r}, \phi, \mathrm{x})\right)}{\partial \phi} \Omega = \dot{m}'_{Regularised}(r)}$$

Gaussian kernel property of zero mean for $\frac{\partial}{\partial \phi}$

Fast Non-Empiric Prediction Model

RANS AD Solution



LEE

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' \mathbf{U_0} + \rho_0 \mathbf{u}') = \dot{\theta}'$$

Modelled Rotor Fluid Displacement

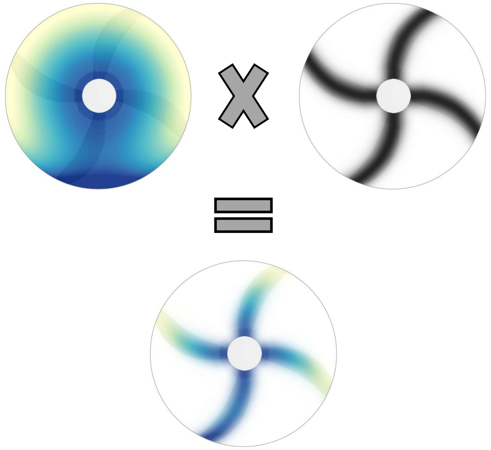
Modelled Rotor Loading

$$\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u}' \cdot \nabla)\mathbf{U_0} + (\mathbf{U_0} \cdot \nabla)\mathbf{u}' + \frac{\nabla p'}{\rho_0} - \rho' \frac{\nabla p_0}{\rho_0^2} = \frac{\boldsymbol{f}'}{\rho_0}$$

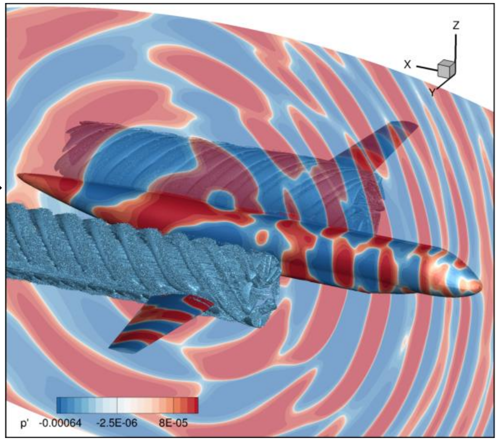
$$\frac{\partial \mathrm{p}'}{\partial t} + \mathbf{u}' \cdot \nabla \mathrm{p}_0 + \mathbf{U_0} \cdot \nabla \mathrm{p}' + \gamma p_0 \nabla \cdot \mathbf{u}' + \gamma p' \nabla \cdot \mathbf{u_0} = \frac{c_0^2}{\gamma} \dot{\theta}'$$

Rotor Noise Source Model

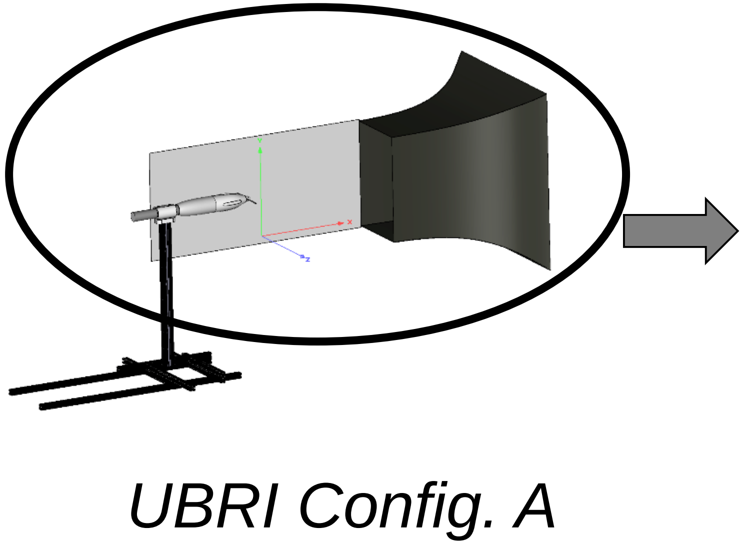
Actuator Disc (AD) based model



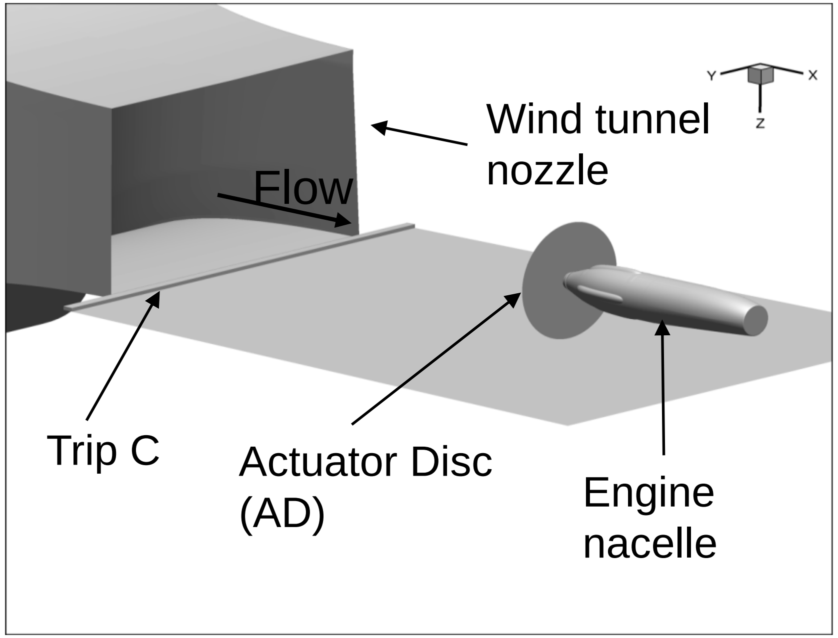
CAA Solution

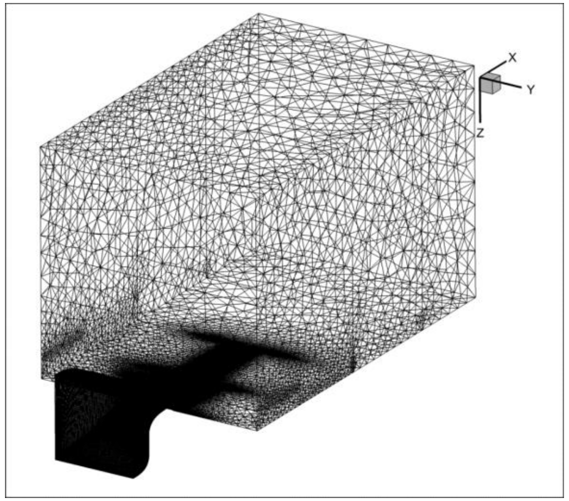


Application Test Case (ENODISE Config. A)

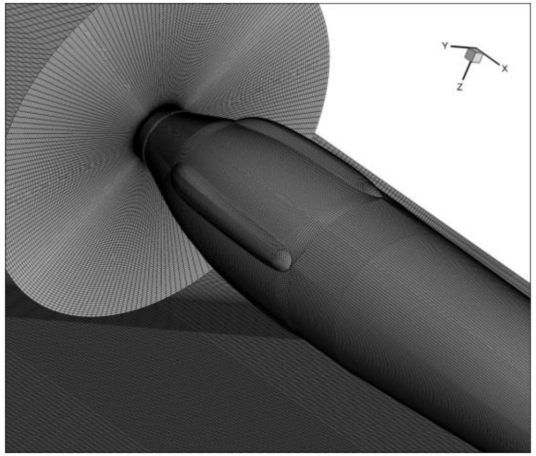


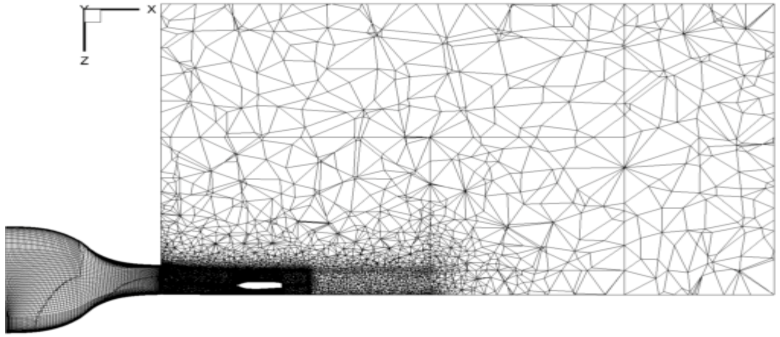
RANS Setup

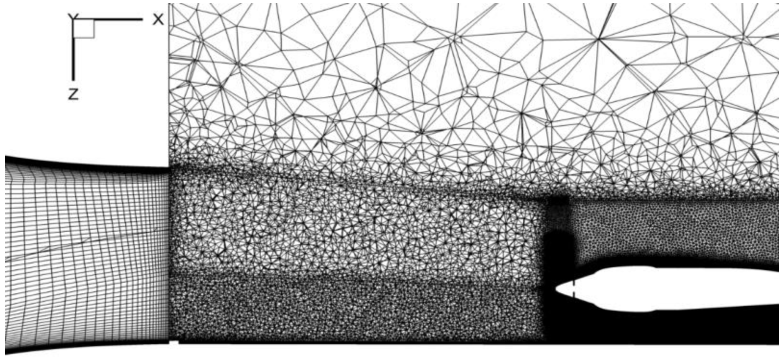




TAU AD RANS MESH PARAMETERS	
CFD mesh size	15E6 mesh cells
CFD domain dimensions	10 x 5.3 x 5.5 [m]
Turbulence Model	k-ω Menter SST
Tip clearance t	5 mm (1/30 R)
Trip type	C: 25 x 10 mm (W x H)
CPU Hours	3100

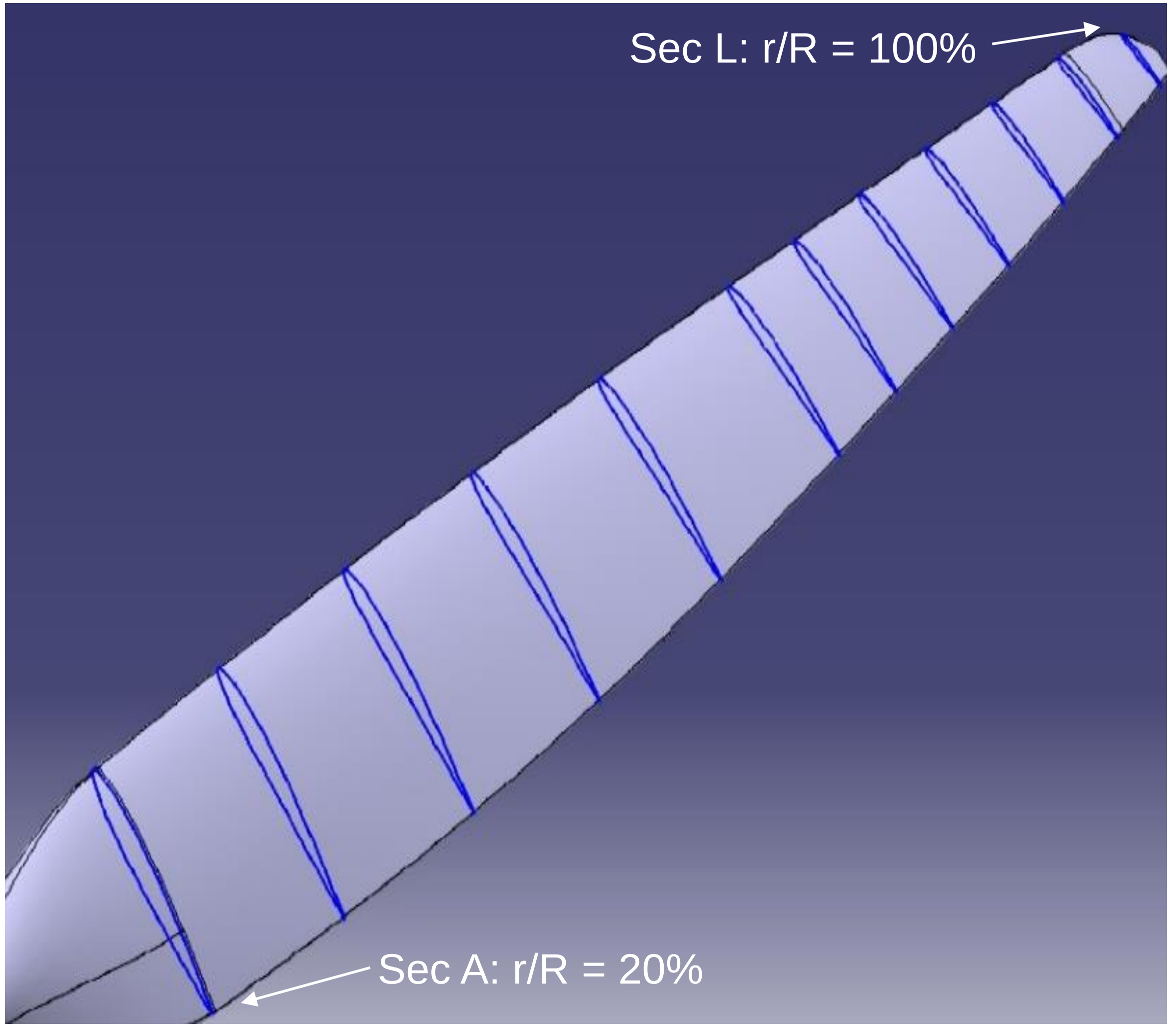






Application Test Case (ENODISE Config. A)

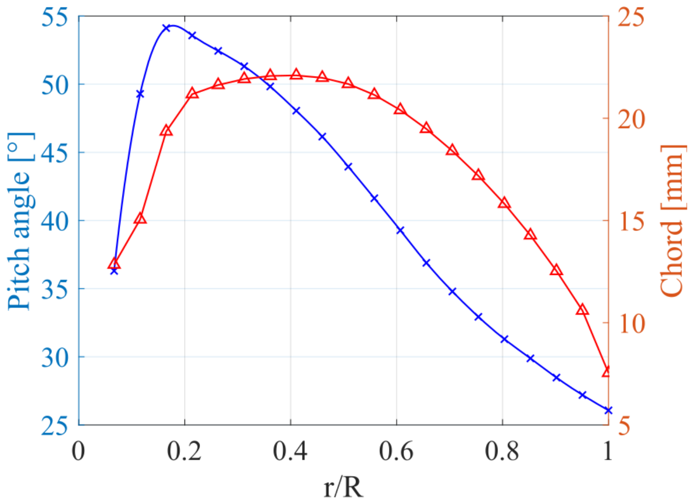
RANS Setup (Propeller Blade)



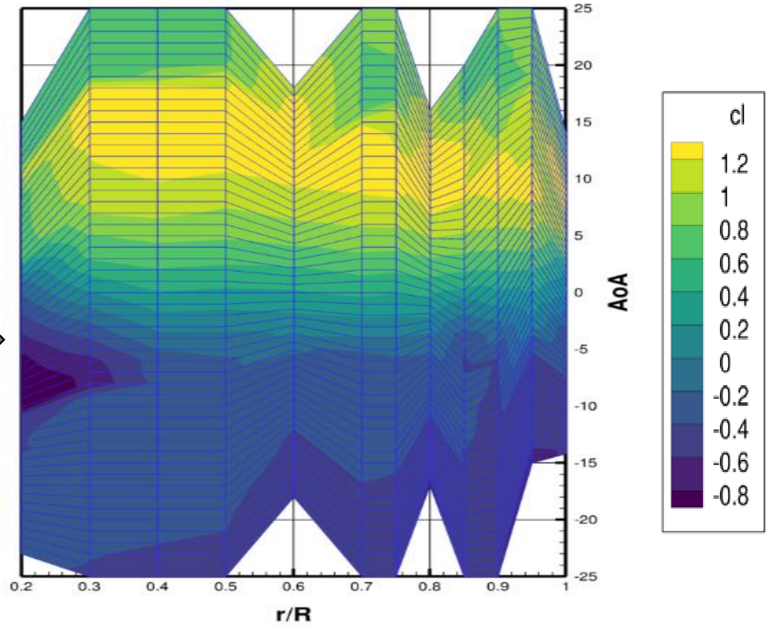
12 Radial sections

- Sec A: r/R = 20%
- Sec B: r/R = 30%
- Sec C: r/R = 40%
- Sec D: r/R = 50%
- Sec E: r/R = 60%
- Sec F: r/R = 70%
- Sec G: r/R = 75%
- Sec H: r/R = 80%
- Sec I: r/R = 85%
- Sec J: r/R = 90%
- Sec K: r/R = 95%
- Sec L: r/R = 100%

12x18" Mejzlik blade
Pitch Angle & Chord Length

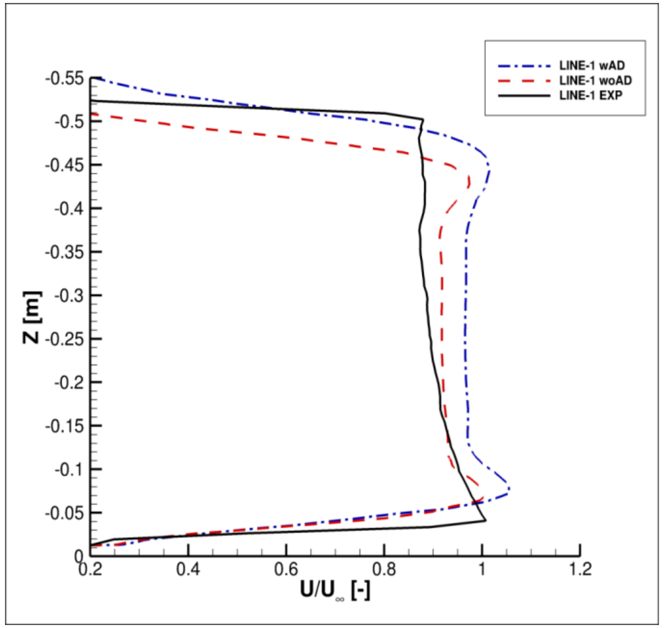


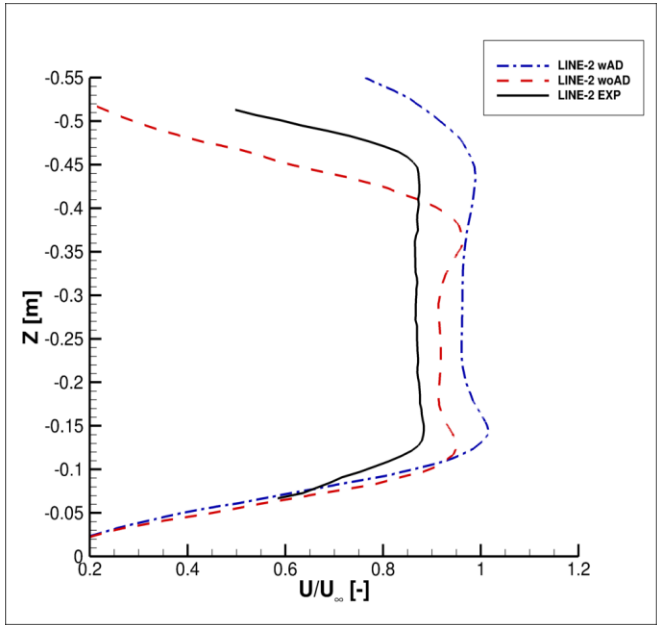
Lift and Drag Coeff. Input for AD RANS model computed with XFOIL

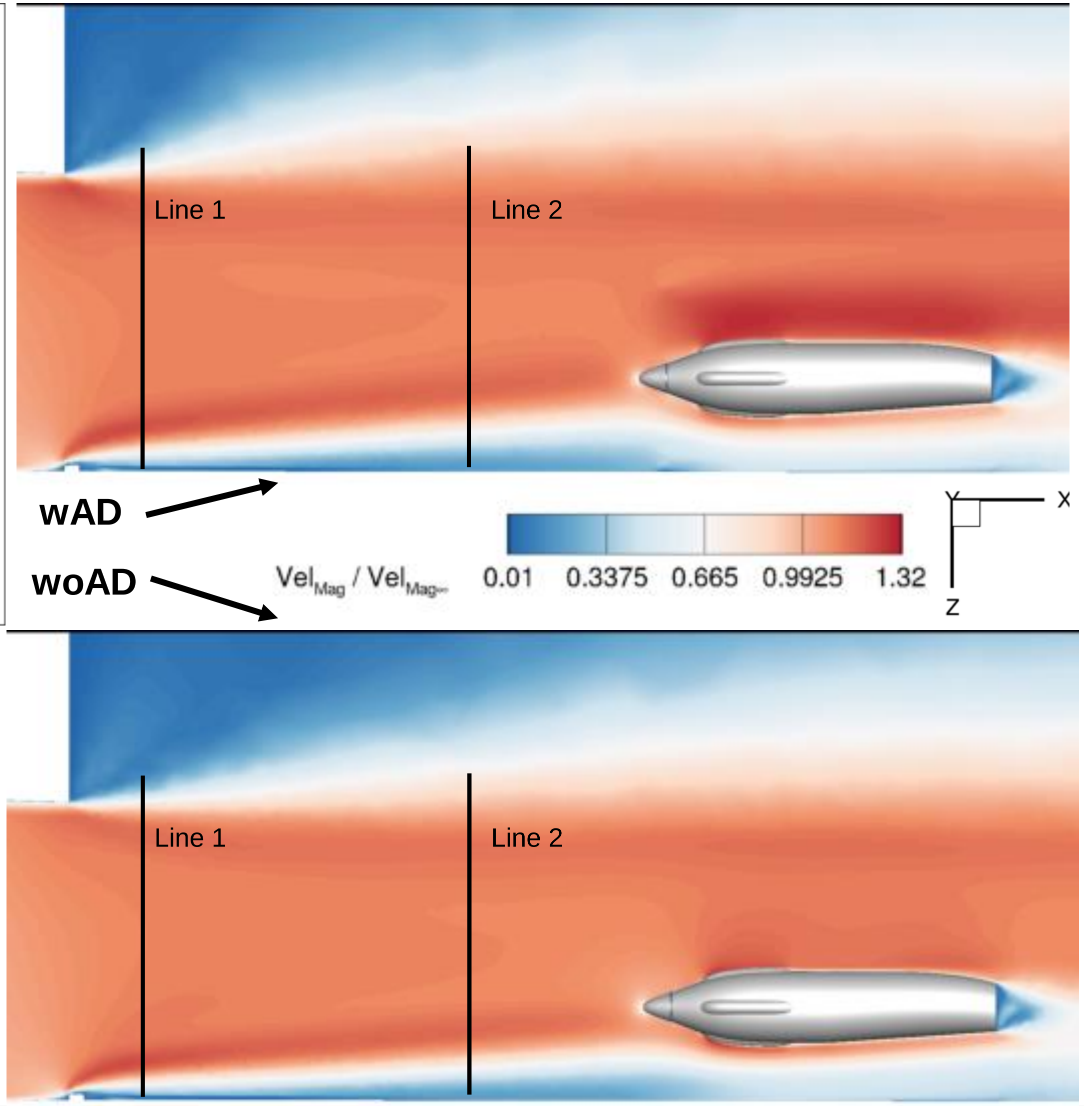


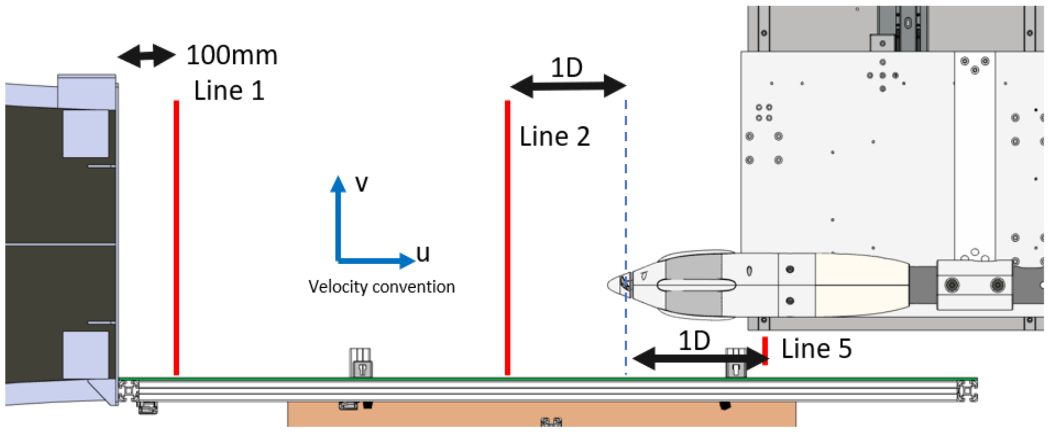
Application Test Case (ENODISE Config. A)

RANS Setup Results









Application Test Case (ENODISE Config. A)

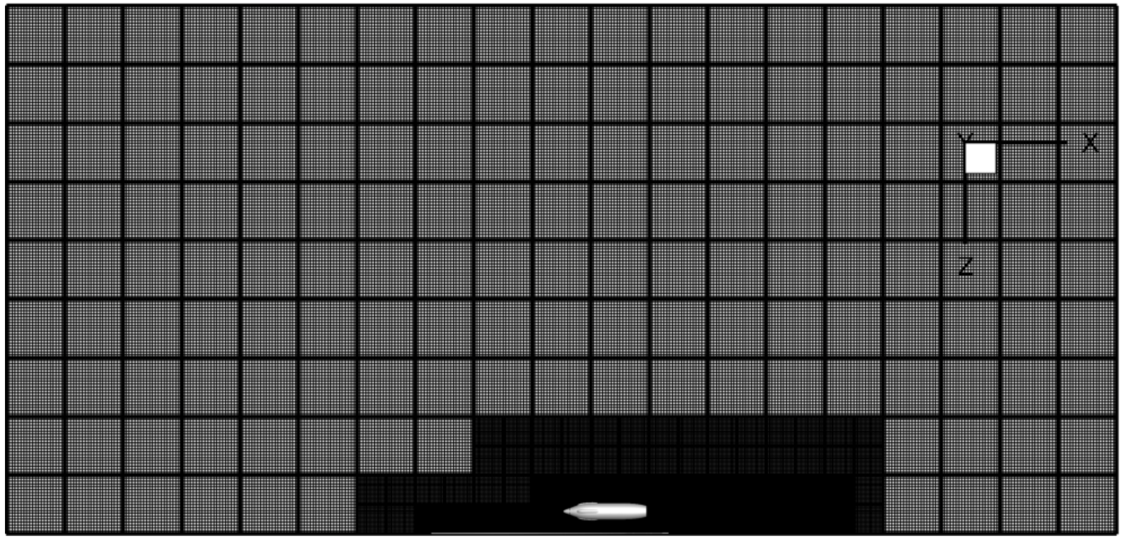
RANS Setup Results

RANS AD RESULTS	EXPERIMENTAL SETUP (UBRI)
Revolutions Per Minute RPM = 6500	Revolutions Per Minute RPM = 6500
Blade Passing Frequency = 108.333 Hz	Blade Passing Frequency = 108.333 Hz
Advance Ratio J = 1	Advance Ratio J = 1
Wind Tunnel Nozzle Outlet Velocity U_∞ = 33 m/s	Wind Tunnel Nozzle Outlet Velocity U_∞ = 33 m/s
Thrust Actuator Disc = 10.606 N	Thrust Propeller = 10.198 N
Torque Actuator Disc = -0.625 Nm	Torque Propeller = -0.605 Nm
Thrust Coeff. Actuator Disc = 0.08496	Thrust Coeff. Propeller = 0.08165
Mass Flow Wind Tunnel Nozzle Inlet = 16.082 kg/s	-
Mass Flow Actuator Disc = 2.884 kg/s	-
Tip clearance t = 5 mm (1/30 R)	Tip clearance t = 5 mm (1/30 R)
Trip C : 25 x 10 mm (W x H)	Trip C : 25 x 10 mm (W x H)

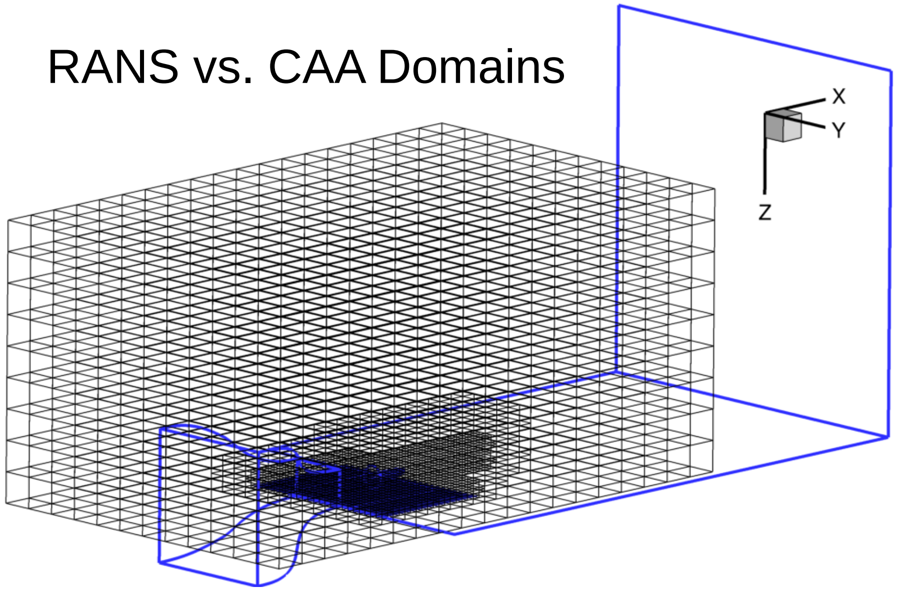
Application Test Case (ENODISE CONFIG. A)

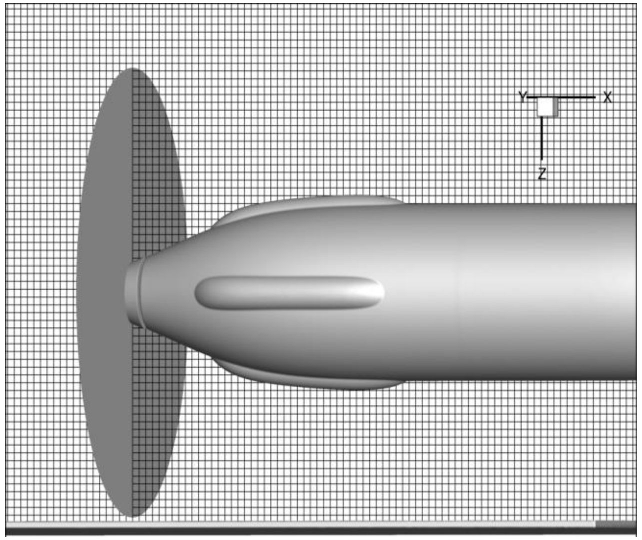
PIANO CAA MESH PARAMETERS	
CAA mesh size	32E6 mesh points
CAA domain	7.9 x 5.0 x 3.8 [m]
Freq. Resol.	Up to 3KHz
BPF	108.333 Hz
Tip clearance t	5 mm (1/30 R)
CPU Hours	6700

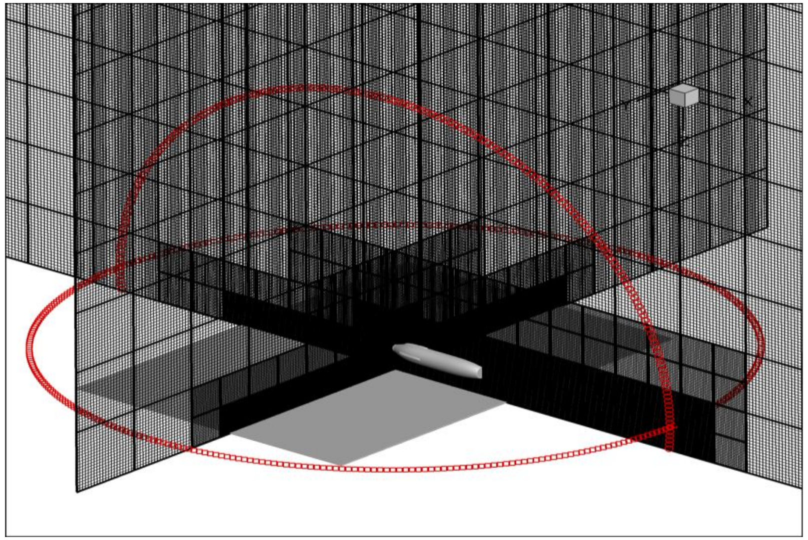
CAA Setup



RANS vs. CAA Domains

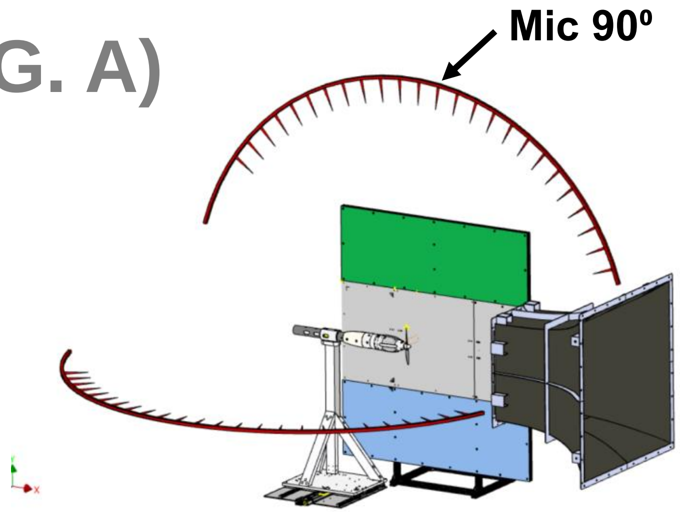




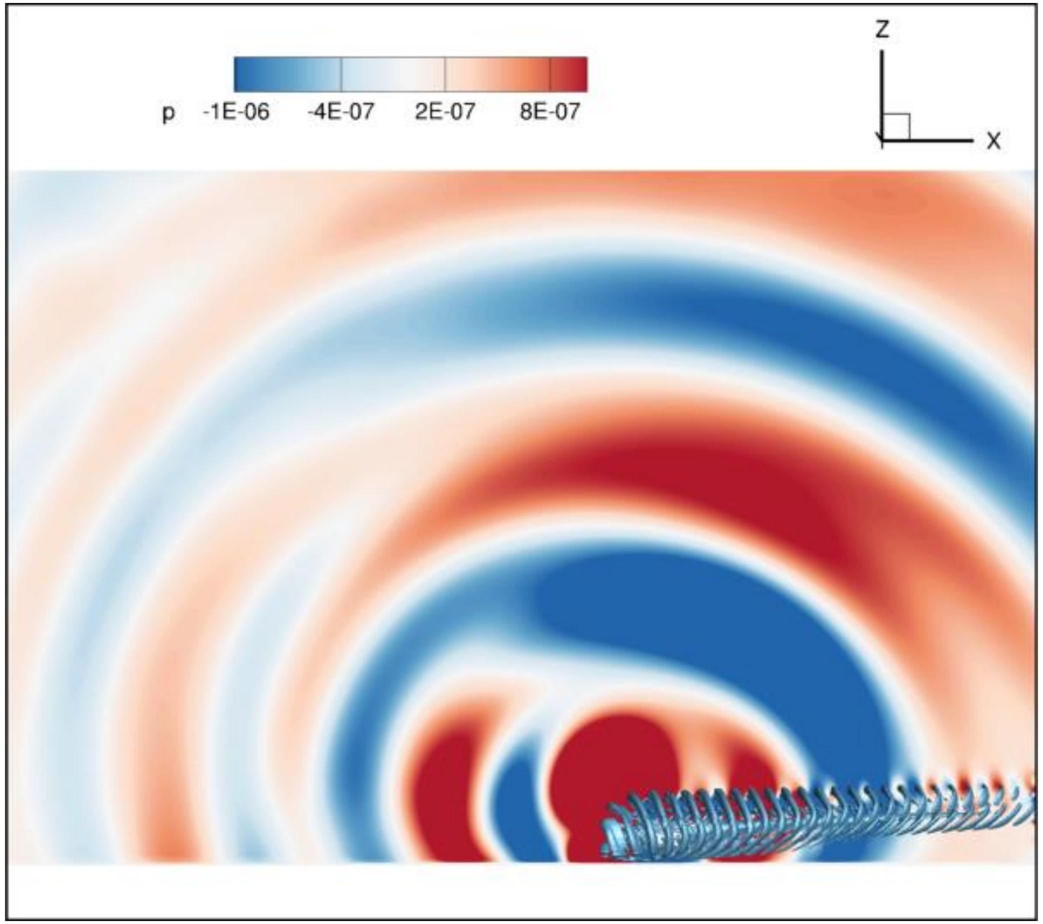


Application Test Case (ENODISE CONFIG. A)

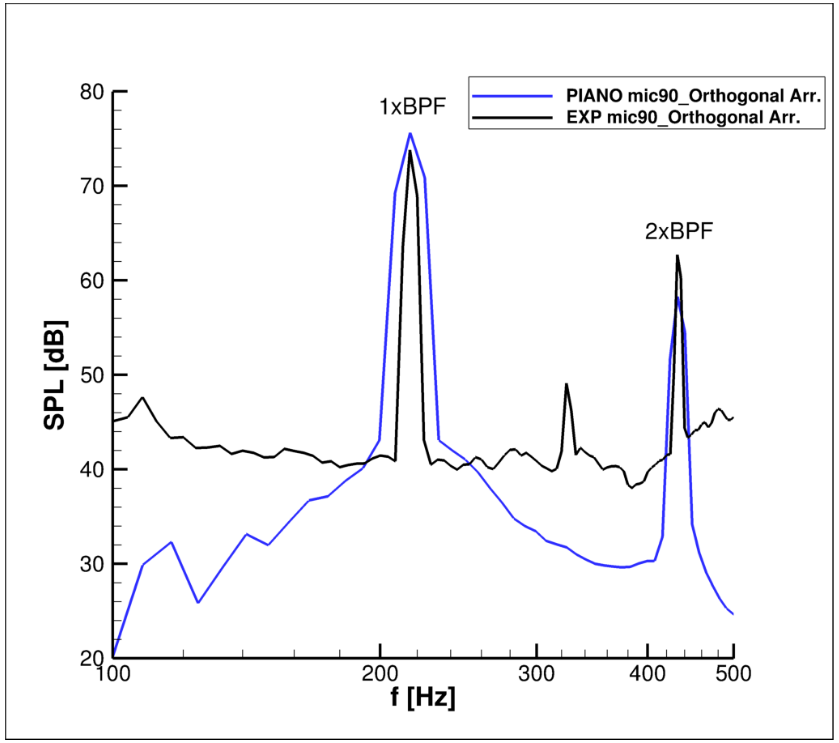
CAA Setup Results



Pressure Fluctuations Contour Plot

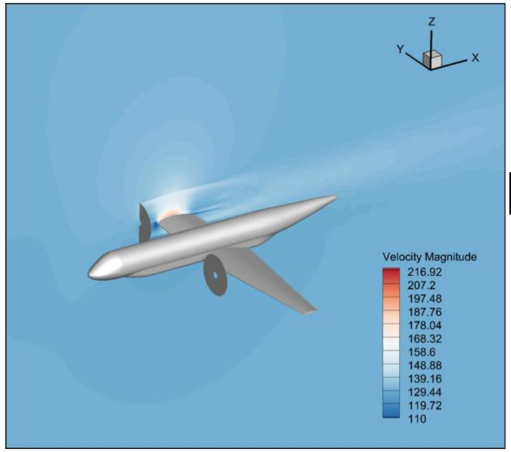


Sound Pressure Level Mic 90º



Fast Non-Empiric Prediction Model

RANS AD Solution



APE+VCE

$$\frac{\partial p'}{\partial t} + c_0^2 \nabla\cdot\left(\mathbf{U_0}\frac{p'}{c_0^2}+\rho_0\mathbf{u^a}\right) = -c_0^2\nabla\cdot(\rho_0\mathbf{u^r}) + c_0^2\dot{\theta}'$$

$$\frac{\partial \mathbf{u^a}}{\partial t} + \nabla(\mathbf{U_0}\cdot\mathbf{u^a}) + \nabla\left(\frac{p'}{\rho_0}\right) = \mathbf{0}$$

APE

Modelled Rotor Fluid Displacement

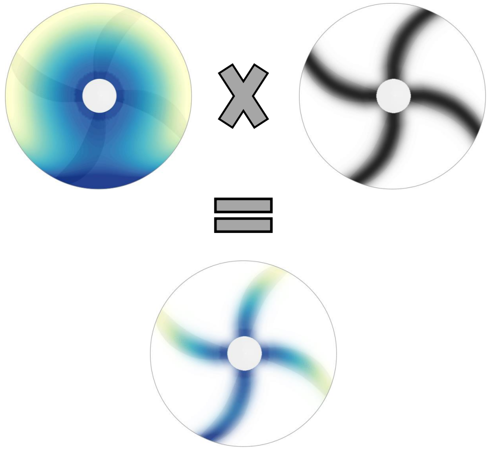
$$\frac{\partial(\rho_0\mathbf{u^r})}{\partial t} + \nabla\cdot(\rho_0\mathbf{U_0}\mathbf{u^r}) = \boldsymbol{f}'$$

Modelled Rotor Loading

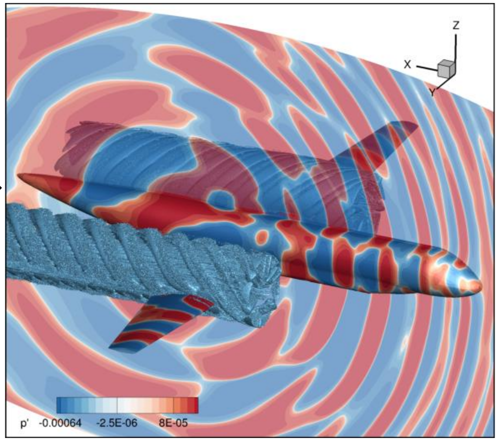
VCE

Rotor Noise Source Model

Actuator Disc (AD) based model



CAA Solution



APE+VCE System Of Equations

- **Linearized Euler Equations** (**LEE**) **numerically not stable in Discontinuous Galerkin (DG)** framework for installed rotor applications
- Replace LEE with Acoustic Perturbation Equations (APE)?
  - APE fail to provide proper directivity (potential loading component not available)
  - **LEE sources cannot be combined with APE**
- Need for alternative to LEE

APE + VCE

$$\frac{\partial p'}{\partial t} + c_0^2 \nabla \cdot \left(\mathbf{U_0} \frac{p'}{c_0^2} + \rho_0 \mathbf{u}^a \right) = \underbrace{-c_0^2 \nabla \cdot (\rho_0 \mathbf{u}^r) + c_0^2 \dot{\theta}'}_{\text{Modelled Rotor Thickness Noise Source}}$$

$$\frac{\partial \mathbf{u}^a}{\partial t} + \nabla(\mathbf{U_0} \cdot \mathbf{u}^a) + \nabla \left(\frac{p'}{\rho_0} \right) = \mathbf{0}$$

(APE)

$$\frac{\partial (\rho_0 \mathbf{u}^r)}{\partial t} + \nabla \cdot (\rho_0 \mathbf{U_0} \mathbf{u}^r) + \cancel{\rho_0 (\mathbf{u}^r \cdot \nabla) \mathbf{U_0}} = \cancel{-\rho_0 \boldsymbol{\omega_0} \times \mathbf{u}^a} + \underbrace{\boldsymbol{f}'}_{\text{Modelled Rotor Force}}$$

(VCE)

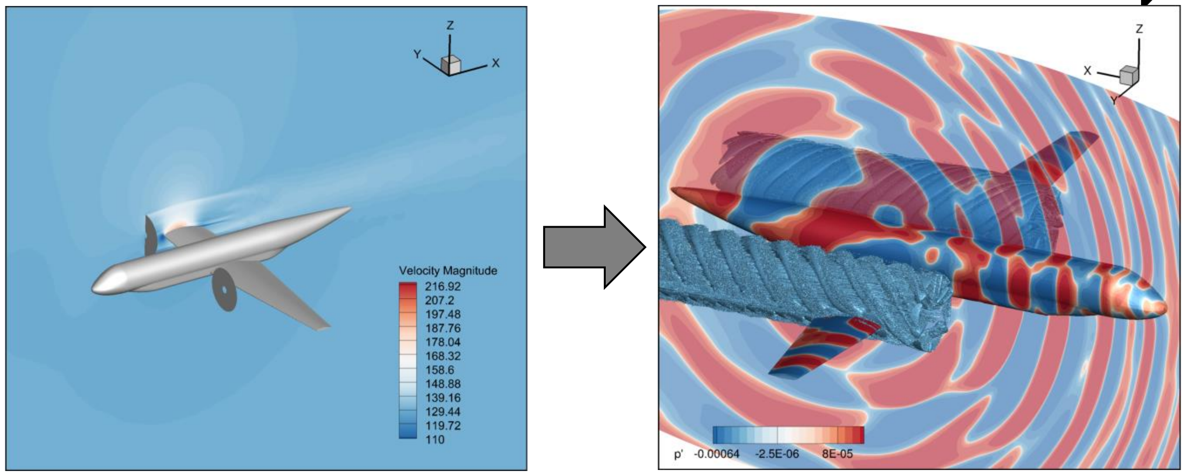
- To avoid hydrodynamic instabilities
  - **Neglect** $\rho_0 (\mathbf{u}^r \cdot \nabla) \mathbf{U_0}$
- **Acoustics/Entropy** feedback $\rho_0 \boldsymbol{\omega_0} \times \mathbf{u}^a$
  - **Negligible for** rotor **installation noise** cases
- Numerical instabilities?
  - **Apply limiter to VCE (convection equation)**

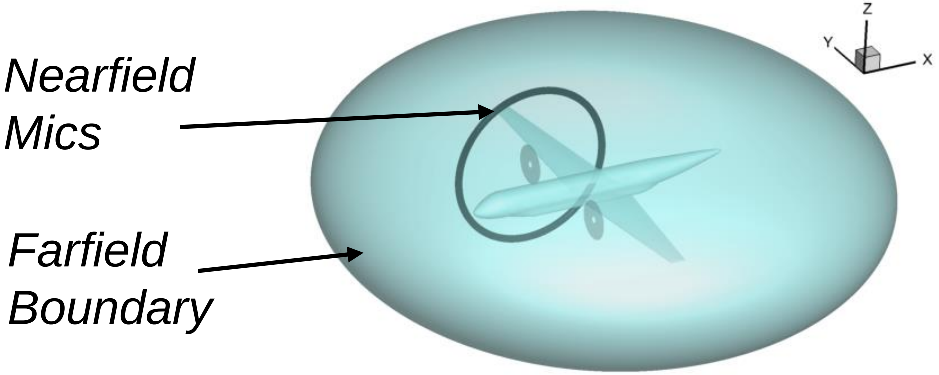
- Derived from Isentropic LEE, through decomposition of $\mathbf{u}' = \mathbf{u}^a + \mathbf{u}^r$ velocities
  - **APE** as main **acoustic governing equations**
  - **Vortical Convection Equations** (VCE) as main **hydrodynamic governing equations**
  - Non distinct eigenmodes
    - Suitable for hydrodynamic - acoustic interaction of installation related noise applications

Application Test Case (SE2A Short Range Aircraft)

Input Parameter	Value (Cruise, Climb)
Free-stream Mach nr. M_∞	(0.42, 0.21)
Free-stream Air Density ρ_∞	(0.57, 1.19) kgm−3
Free-stream Speed Of Sound	(311.0, 340.0) ms-1
Number of Blades	(6, 6)
Tip Mach Number M_{Tip}	(0.47, 0.6)
Propeller Blade Length	(2.05, 2.05) m
Revolutions Per Minute RPM	(820, 1100)
Thrust Single Propeller	(6.4, 19.5) kN
Number of Propellers	(2, 2), TU Delft Xprop

AD RANS **CAA**





CAA Setup

Cases simulated (including background AD RANS mean flow of full aircraft):

- Climb, Counter-Rotating Props, Positive Y Prop only
- Climb, Counter-Rotating Props, Negative Y Prop only
- Climb, Co-Rotating Props, Positive Y Prop only
- Climb, Co-Rotating Props, Negative Y Prop only
- Cruise, Counter-Rotating Props, Positive Y Prop only
- Cruise, Counter-Rotating Props, Negative Y Prop only
- Cruise, Co-Rotating Props, Positive Y Prop only
- Cruise, Co-Rotating Props, Negative Y Prop only

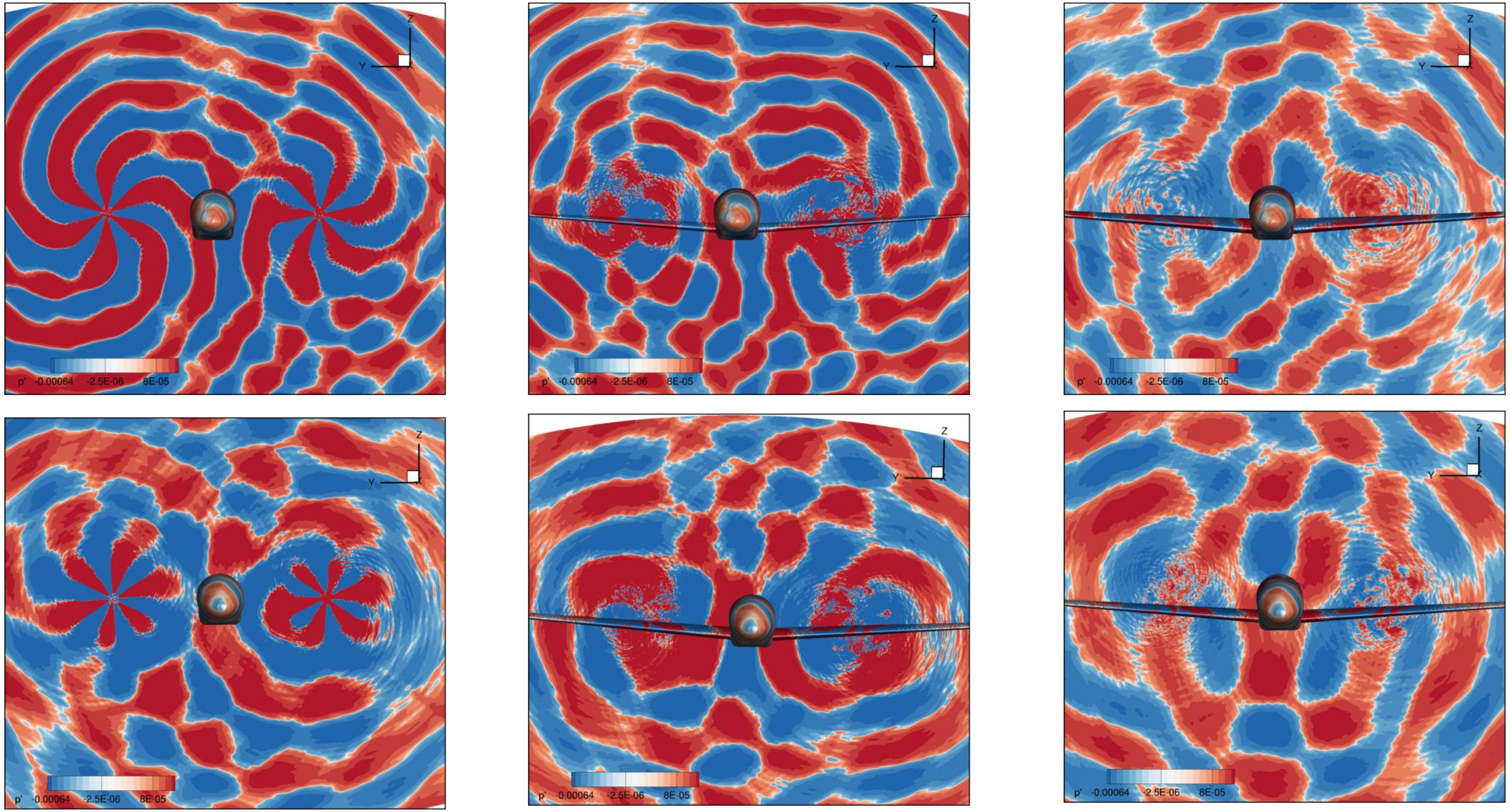
Application Test Case (SE2A Short Range Aircraft)

Pressure Fluctuations Contour Plots, Counter-Rotating Props

Prop Plane | **Leading Edge** | **Trailing Edge**

Climb-case

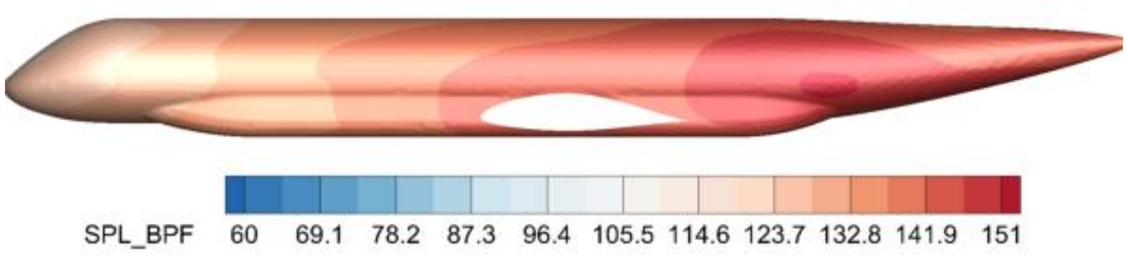
Cruise-case



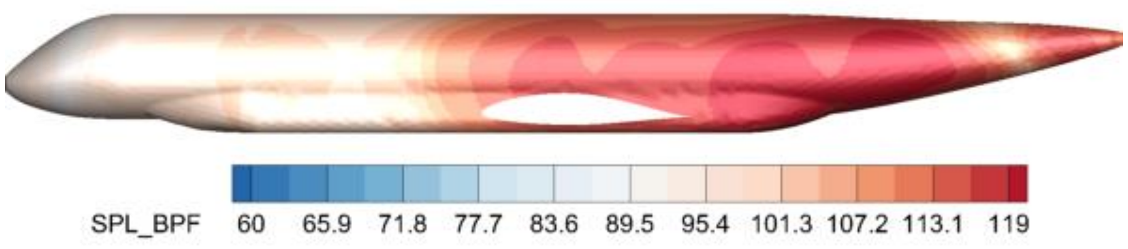
Application Test Case (SE2A Short Range Aircraft)

Sound Pressure Level Contour Plots of the Blade Passing Frequency

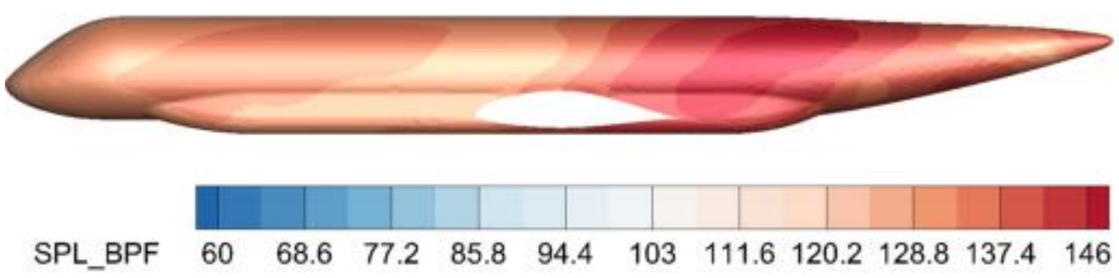
Climb-case, Counter-Rotating Props



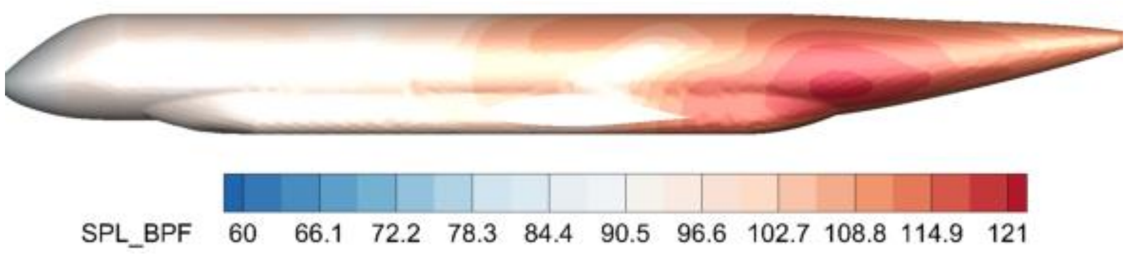
Cruise-case, Counter-Rotating Props



Climb-case, Co-Rotating Props



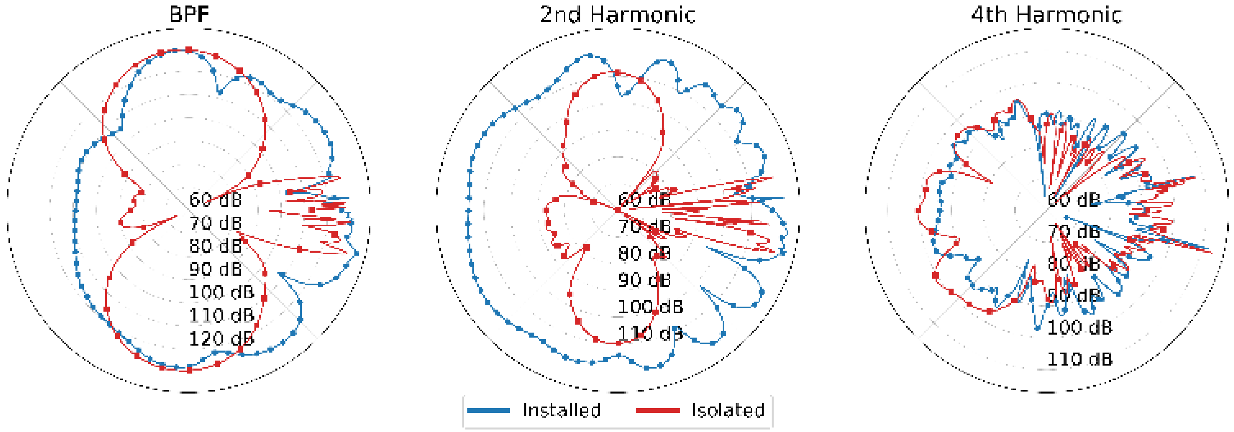
Cruise-case, Co-Rotating Props



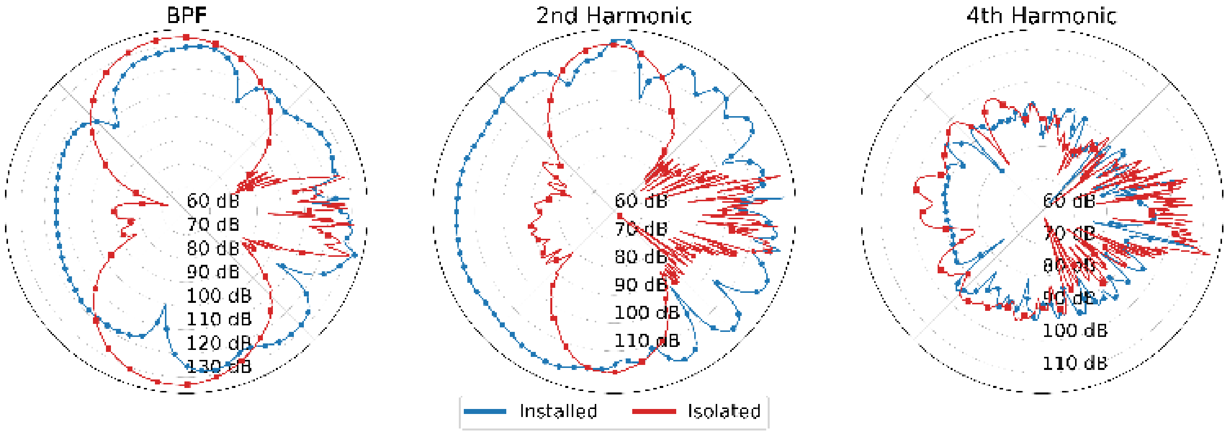
Application Test Case (SE2A Short Range Aircraft)

Sound Pressure Level @ Distance = 4 Propeller Blade Length, x-z plane, Rotor Loading Noise, Single Propeller

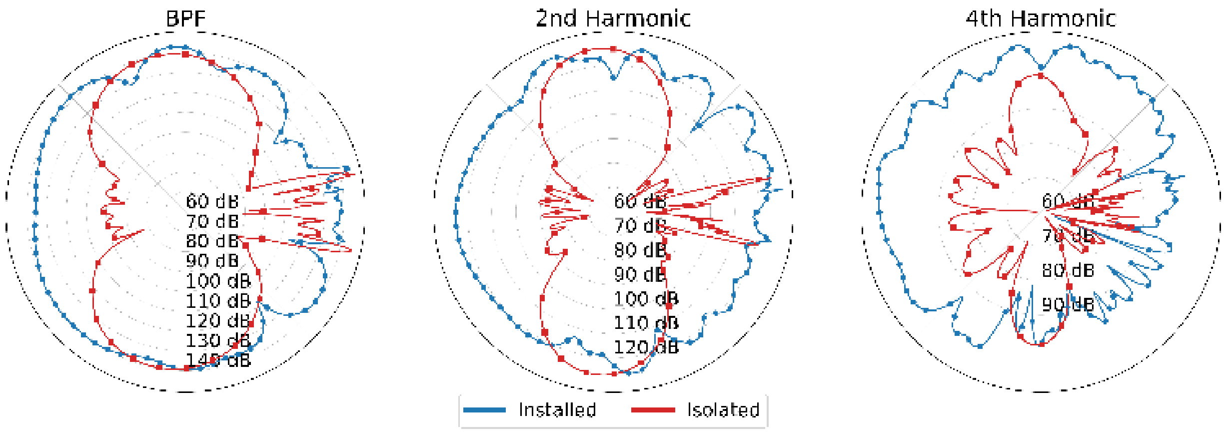
Cruise-case, Counter-Rotating Props



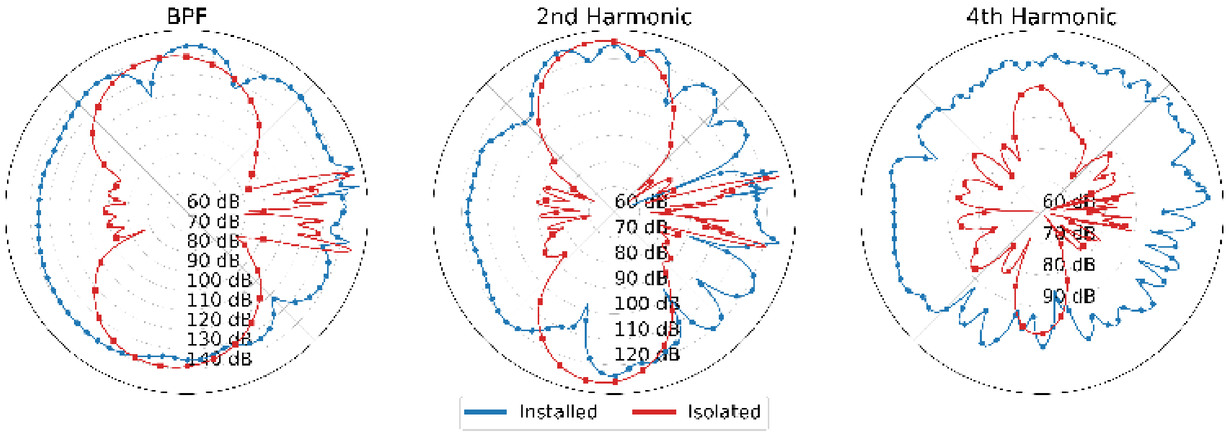
Cruise-case, Co-Rotating Props



Climb-case, Counter-Rotating Props



Climb-case, Co-Rotating Props

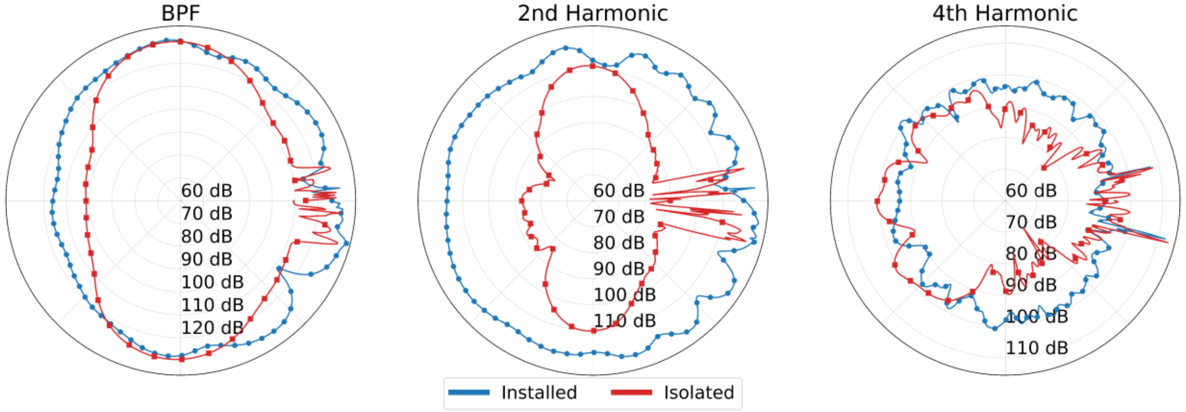


Application Test Case (SE2A Short Range Aircraft)

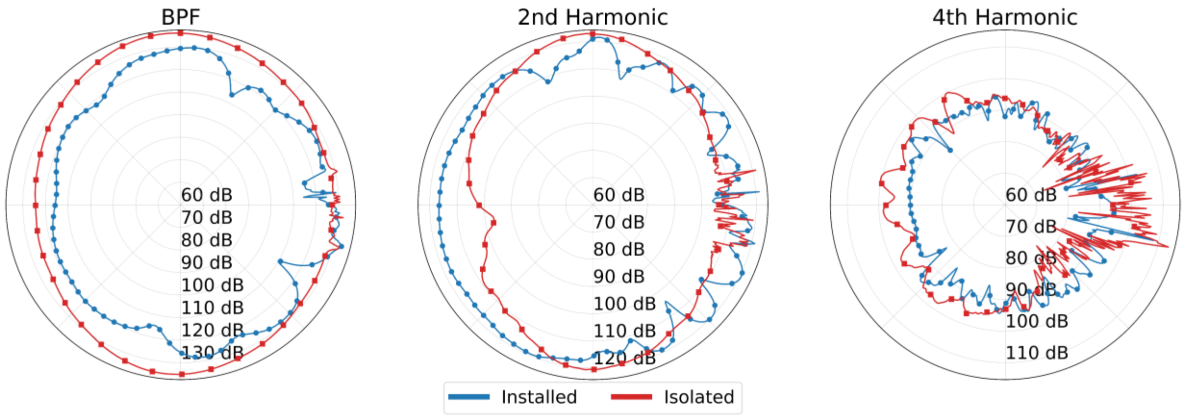
DLR

Sound Pressure Level @ Distance = 4 Propeller Blade Length, x-z plane, Rotor Loading Noise, Two Propellers Combined

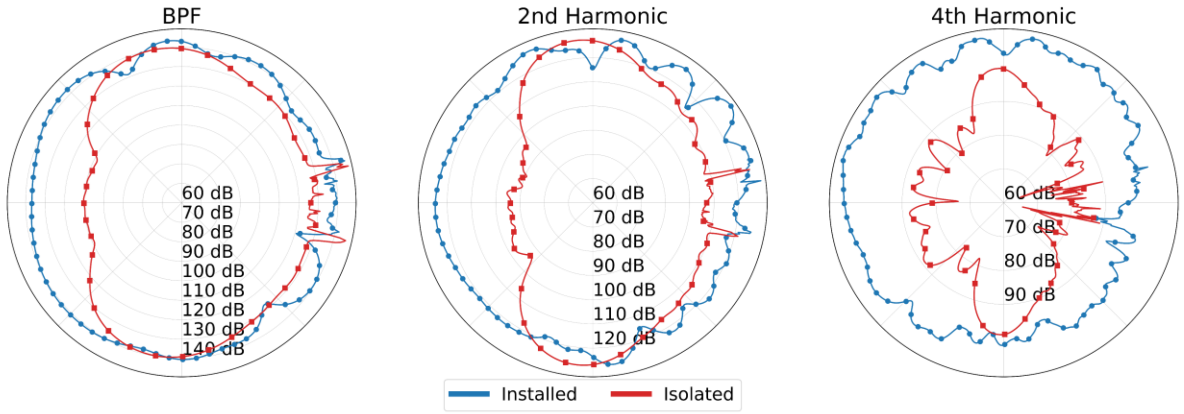
Cruise-case, Counter-Rotating Props



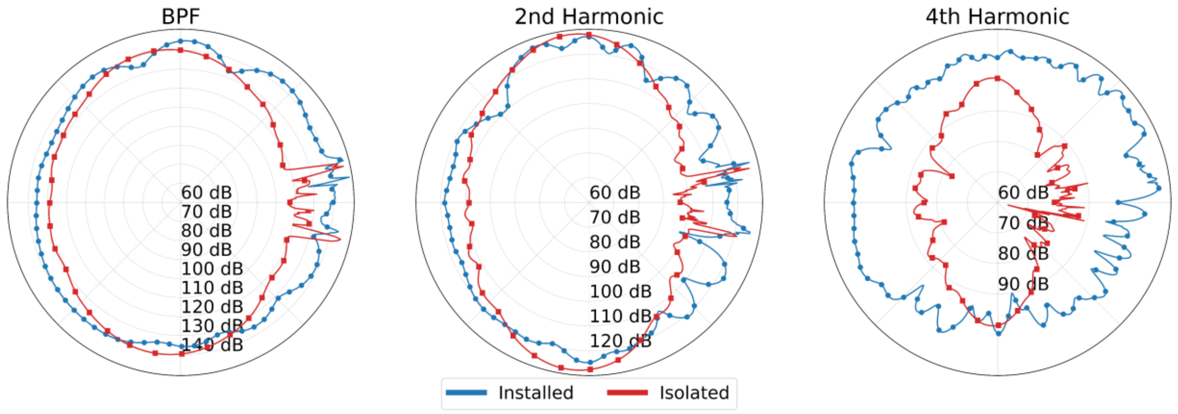
Cruise-case, Co-Rotating Props



Climb-case, Counter-Rotating Props



Climb-case, Co-Rotating Props



Conclusions

- Implementation of **rotor noise model validated** with different test cases
  - **Initial validation with experimental data** shows correct prediction for AD – based model
  - **The model** can also describe well qualitatively the acoustic field of installed propellers on a realistic aircraft
- **LEE or APE+VCE** system of equations **numerically robust** for propulsion installation related noise applications
  - **VCE + Limiters to overcome DG discretization issues of LEE in DISCO++**
  - **Immersed Boundary Method in PIANO provides an efficiency boost to the method**
- Future outlook
  - Inclusion of broadband noise components using FRPM
  - Further validation with available experimental data and higher-fidelity simulations