Unsteady Adjoint Method for Aeroacoustic Propeller Optimization

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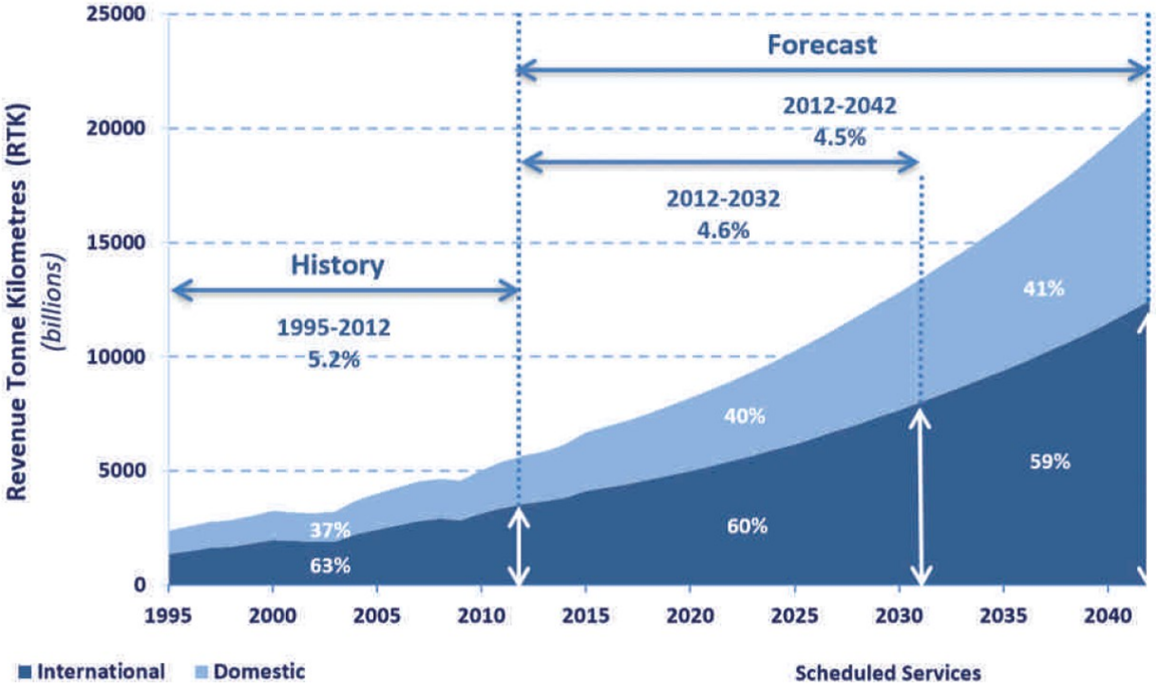
Background



source: https://www.icao.int/Meetings/FutureOfAviation

Can we follow this trend in a sustainable way?

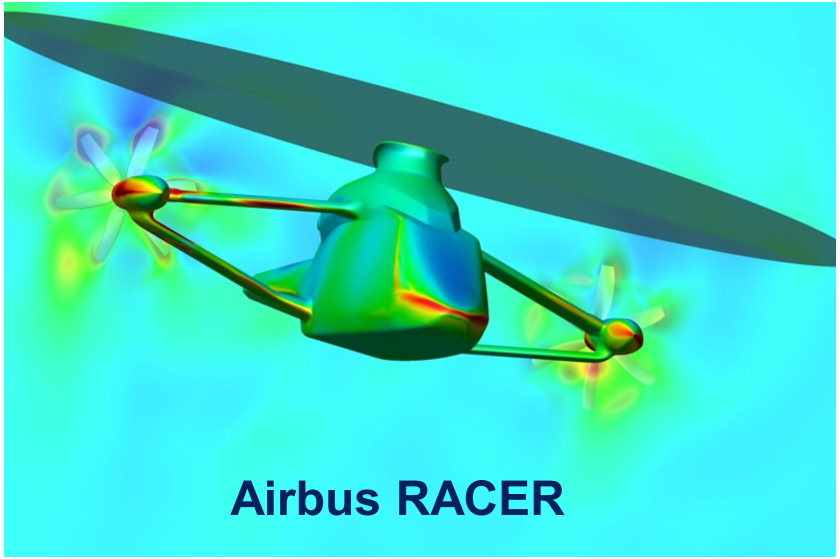
improved propeller design to contribute

ACARE Goals by 2050		Challenges
CO_2 emissions	*-75%*	*Aerodynamics*
NOx emissions	*-90%*	
Perceived noise	*-65%*	*Acoustics*

Challenges by emerging concepts

e.g. unsteady interactional flow due to presence of other components

overhead rotor, box-wing, wing-tip, the other propellers, ...



Source: https://www.cleansky.eu/what-next-in-horizon-europe

Image credits: NASA Langley/Advanced Concepts Lab, AMA, Inc

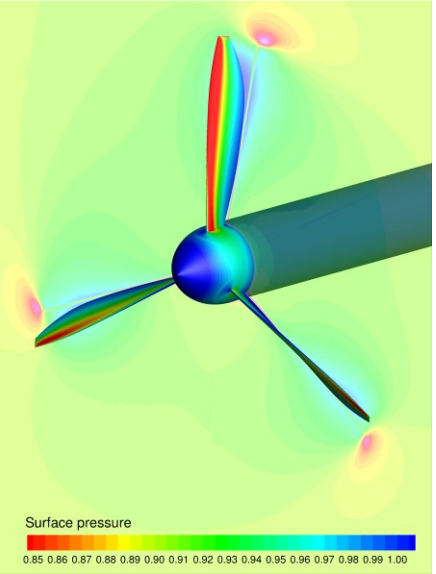
High-Fidelity Analysis Method

Capture the flow (periodic) unsteadiness

URANS CFD

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \vec{\nabla} \cdot \boldsymbol{F}(\boldsymbol{Q}) = 0 \quad \text{in } \Omega,$$

$$B(\boldsymbol{Q}, \boldsymbol{x}, t) = 0 \quad \text{on } S(\boldsymbol{\theta}, t),$$



Time-accurate unsteady flow solution

post-processing surface integrals

Aerodynamics

Thrust

Power

Ffwocs Williams Hawkings

Acoustics

Noise

High-Fidelity Design Optimization Method

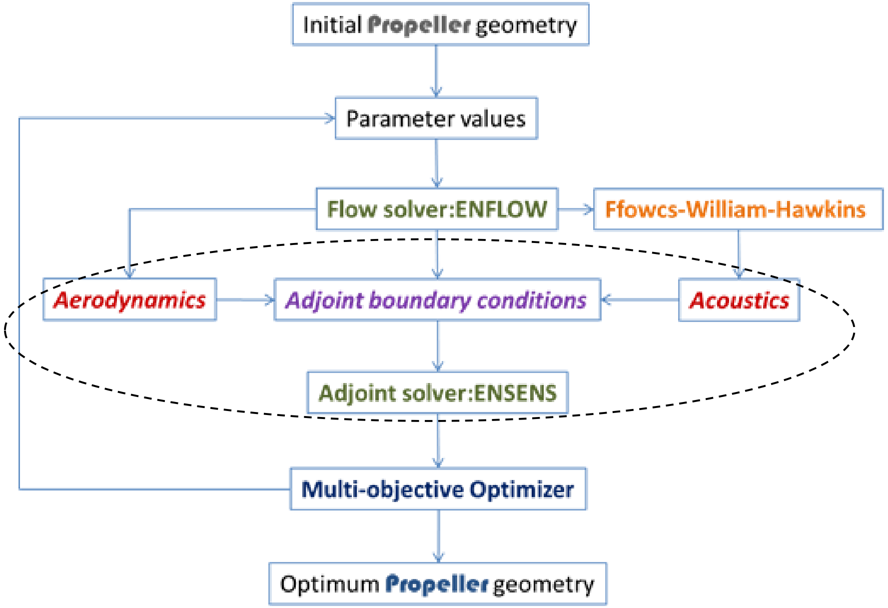
Gradient-based optimization algorithm

- most suitable
  - ✓ Quick yet meaningful improvement
  - ✓ Constrained Multi-objective design

Adjoint method

- most efficient for gradient calculation
  - ✓ High-fidelity models
  - ✓ Large design space

High-Fidelity Design Optimization Method



Focus of development, two-fold:

1. Unsteady adjoint solver with verified aerodynamic and acoustic gradients
2. Affordable Adjoint Solver minimizing storage, I/O loads and CPU time by phase-lagged boundary condition

1. Unsteady Adjoint Problem

Adjoint equations:

$$-\frac{\partial \boldsymbol{\lambda}}{\partial t} - \mathrm{A}^{\mathsf{T}} \cdot \nabla \boldsymbol{\lambda} - \mathrm{Y}^{\mathsf{T}} K = 0 \quad \text{in } \Omega,$$

Adjoint boundary conditions (aerodynamics):

$$\vec{\lambda} \cdot \vec{n} = \frac{\partial \psi}{\partial p} - (\vec{u} \cdot \vec{n})\lambda_5, \qquad \vec{\lambda} \cdot \vec{s} = -\frac{\partial \psi}{\partial \tau_{ws}} - (\vec{u} \cdot \vec{s})\lambda_5, \qquad \vec{\lambda} \cdot \vec{t} = -\frac{\partial \psi}{\partial \tau_{wt}} - (\vec{u} \cdot \vec{t})\lambda_5, \qquad \vec{\nabla}\lambda_5 \cdot \vec{n} = 0.$$

Adjoint boundary conditions (acoustics):

$$\vec{\lambda} \cdot \vec{n} = \frac{1}{|S_i^n|} \frac{\partial I_h}{\partial p_i^n} - (\vec{u} \cdot \vec{n})\lambda_5, \qquad \vec{\lambda} \cdot \vec{s} = -(\vec{u} \cdot \vec{s})\lambda_5, \qquad \vec{\lambda} \cdot \vec{t} = -(\vec{u} \cdot \vec{t})\lambda_5, \qquad \vec{\nabla}\lambda_5 \cdot \vec{n} = 0.$$

1. Unsteady Adjoint Solver Development

<u>Starting-point is an existing steady adjoint solver</u>

steady in rotating frame

steady *solution procedure*

Test-Case

Flow solution

Adjoint solution

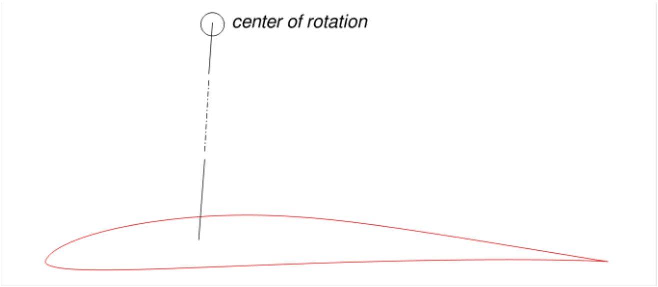
Gradient

unsteady *solution procedure*

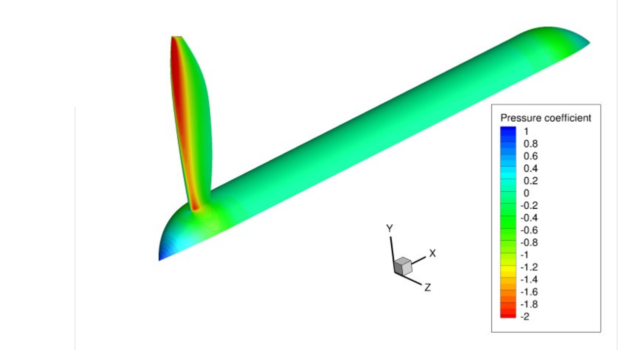
unsteady in inertial frame

1. Unsteady Adjoint Solver Development

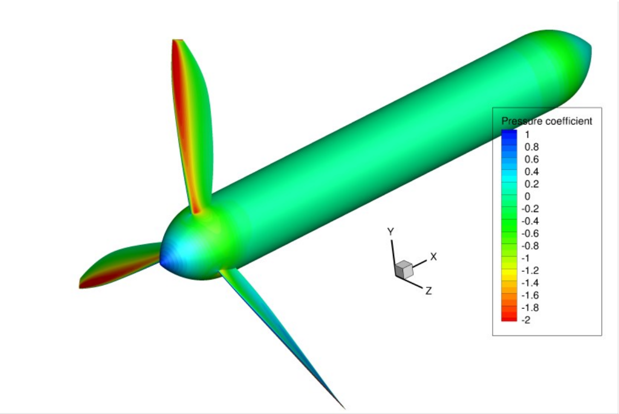
make use of test cases with increasing complexity
from an academic to industrially relevant configuration



Ultra-low Re Eppler E387
rotating in still air



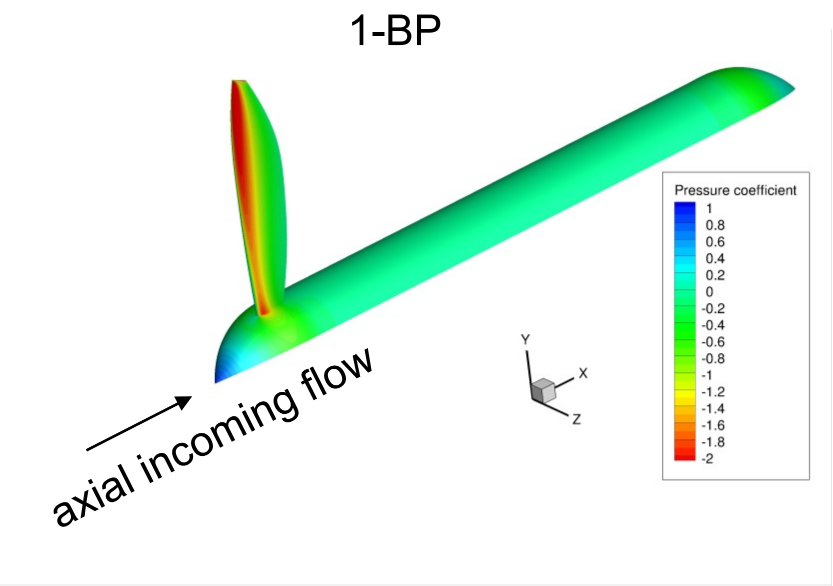
1-BP (Blade Passage)



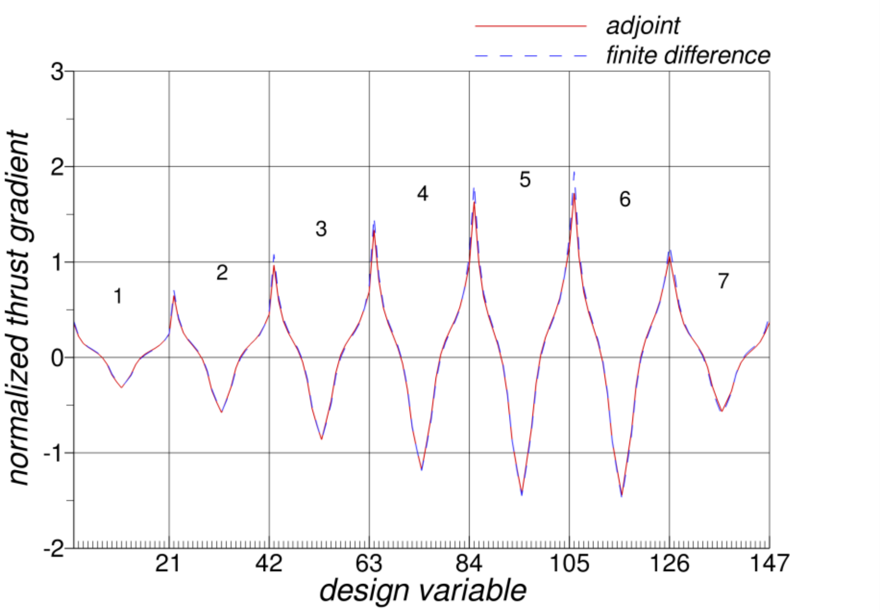
Full 3-BP

ONERA's HAD-1 propeller

1. Unsteady Adjoint Solver Development



steady problem in rotating frame



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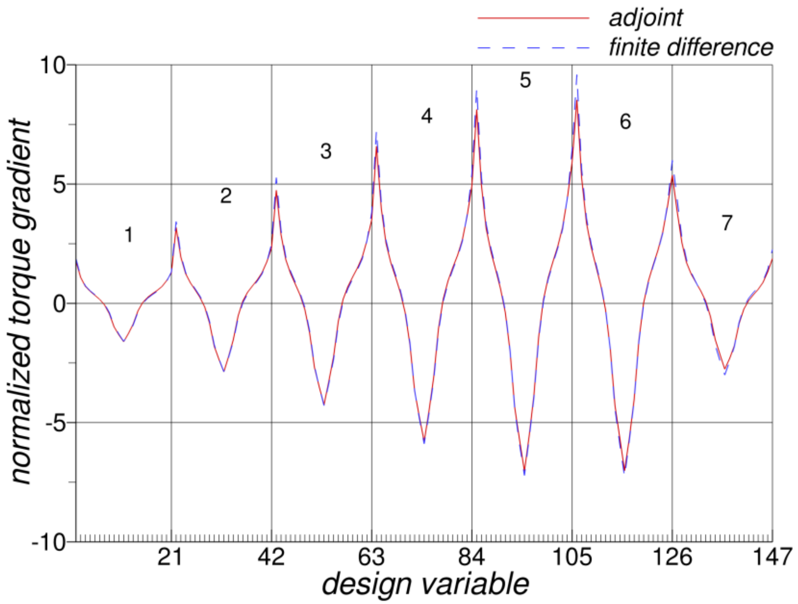
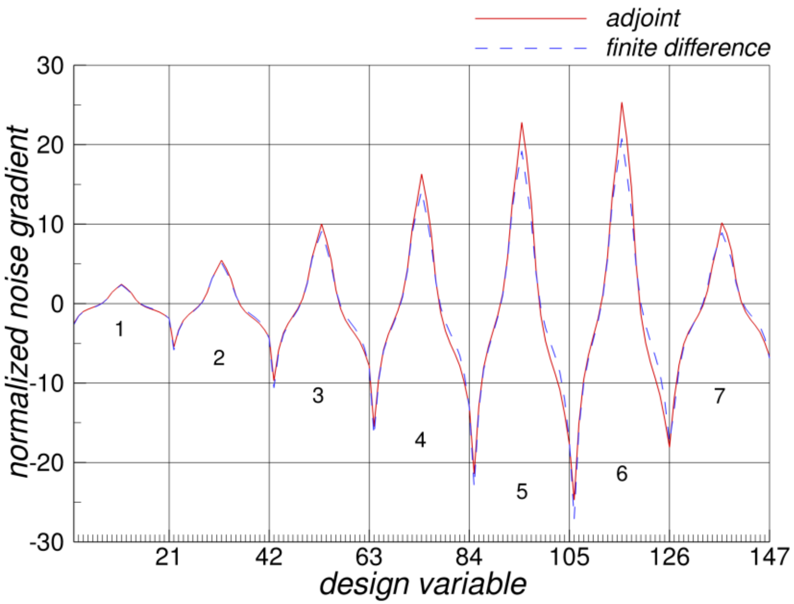
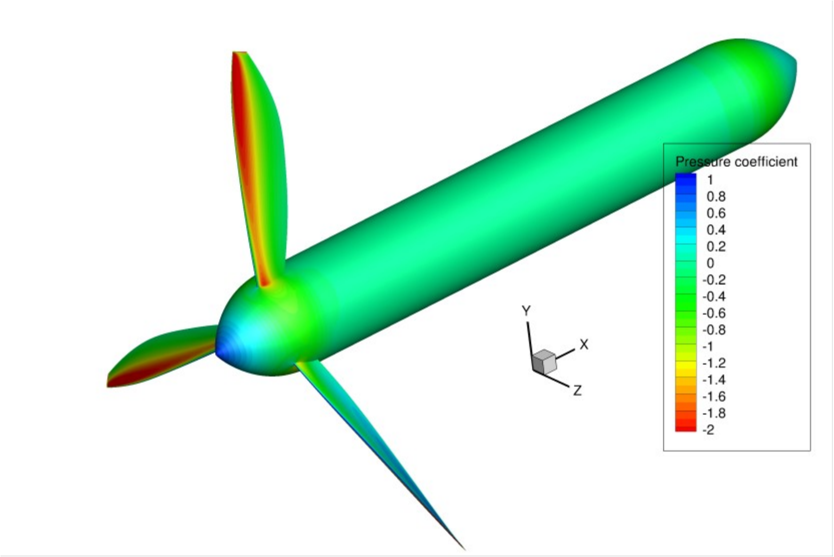
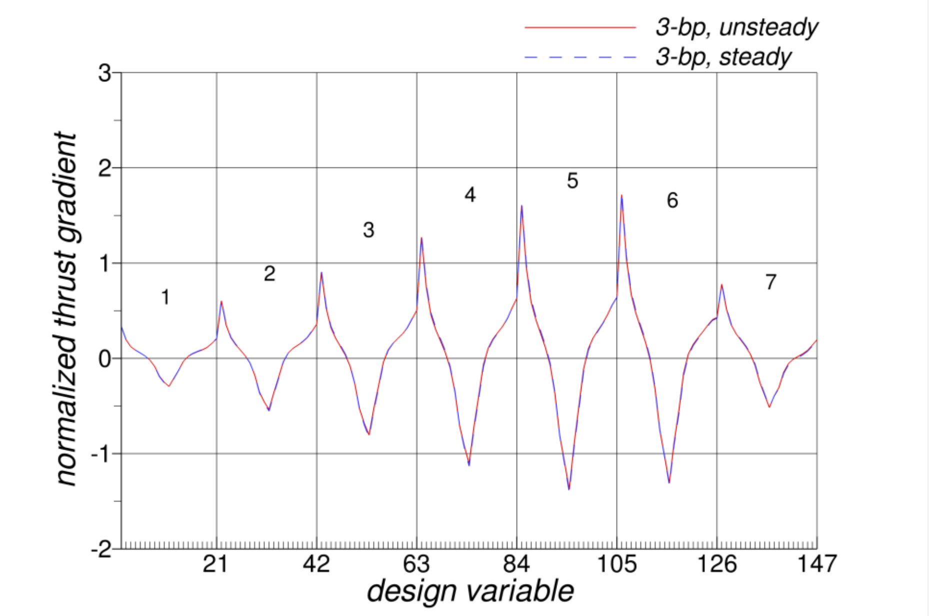




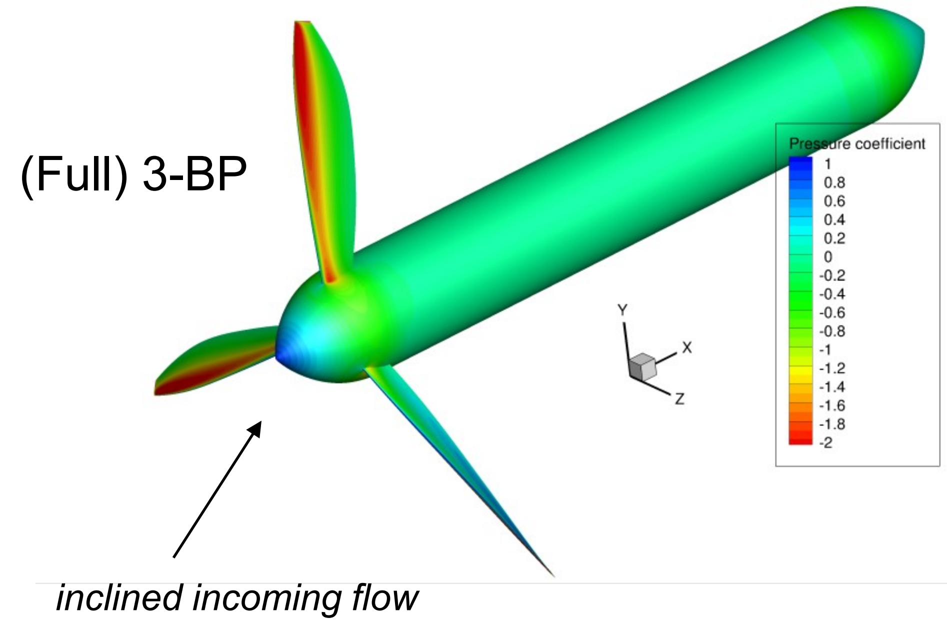
1. Unsteady Adjoint Solver Development

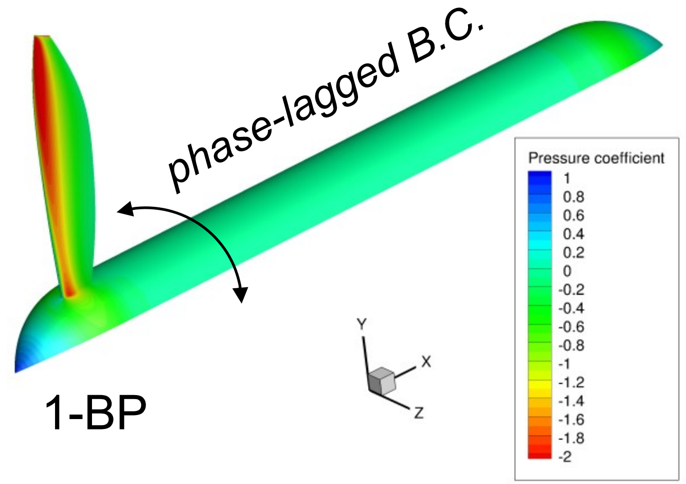




2. Phase-lagged boundary condition

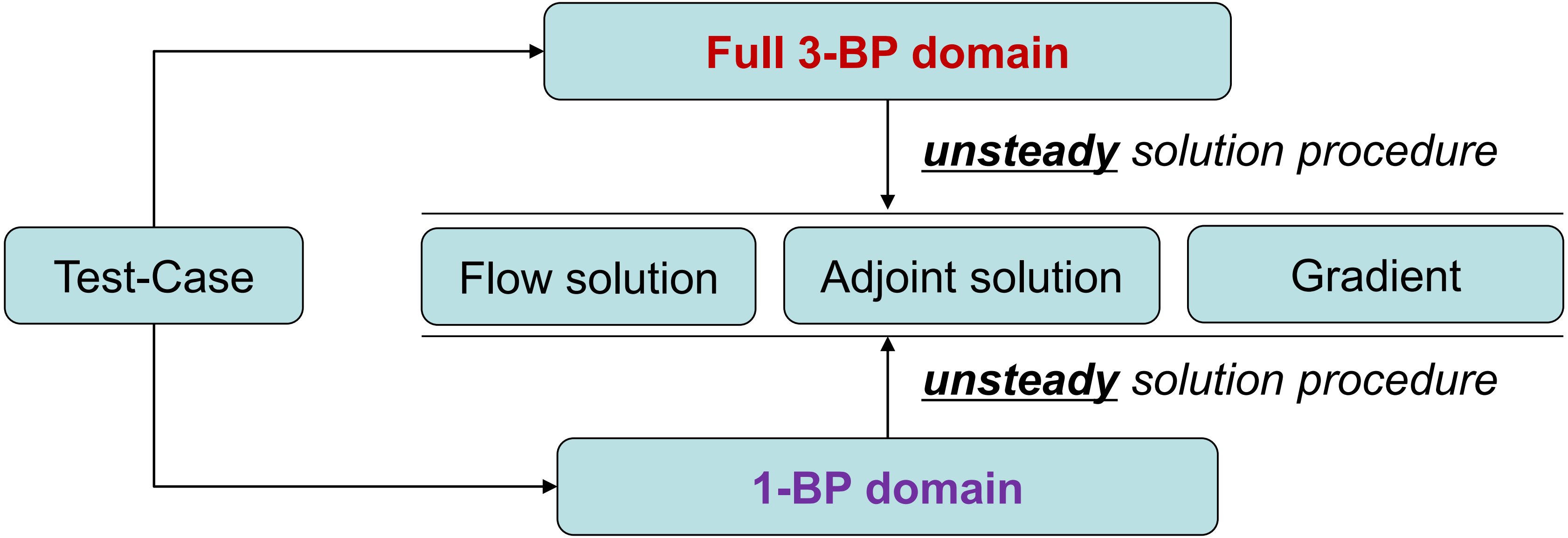
The boundary condition should allow **reduction** of disk storage, I/O loads and CPU time **proportional** to the number of blades





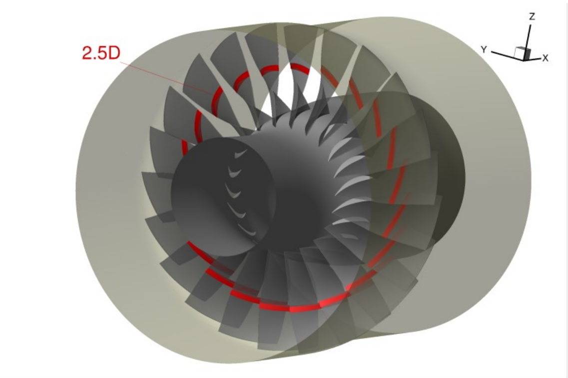
2. Phase-lagged B.C. development

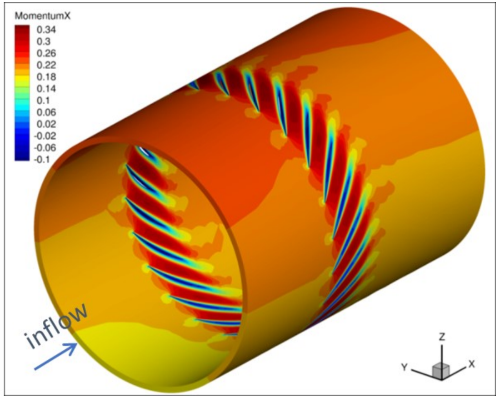
Starting-point is conventional (3-BP) domain



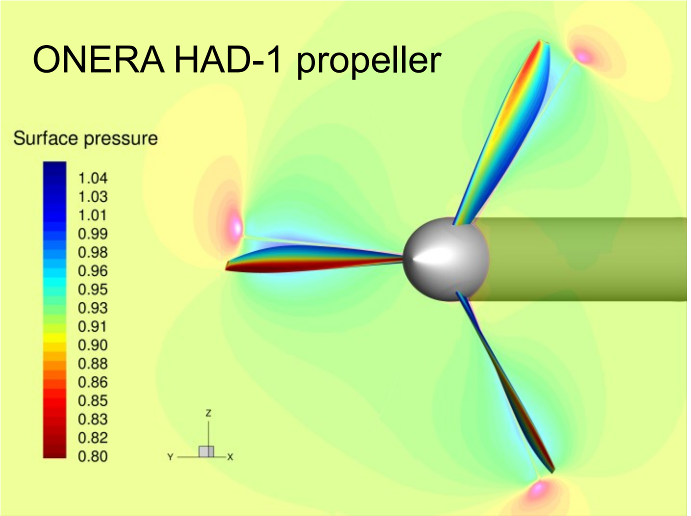
2. Phase-lagged B.C. developement

test cases with increasing complexity
from academic to industrially relevant configuration

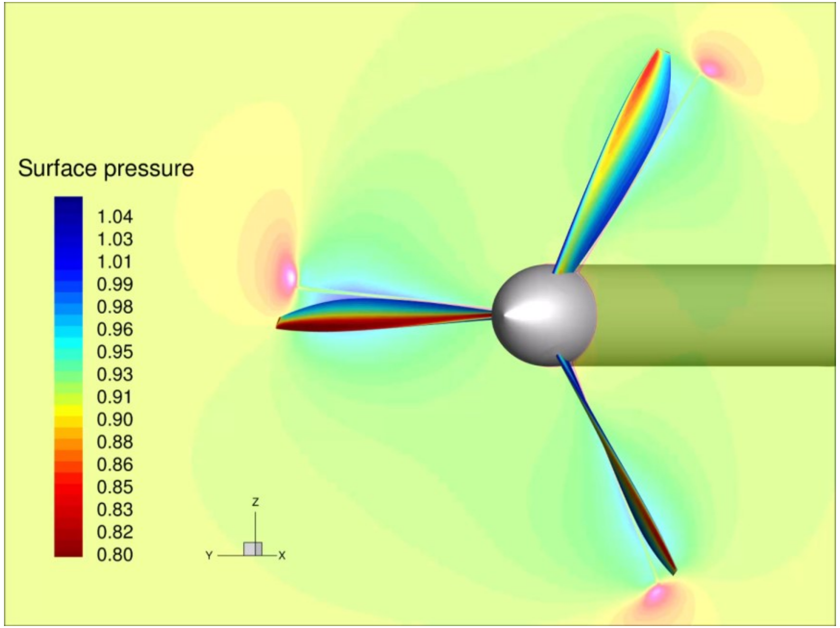




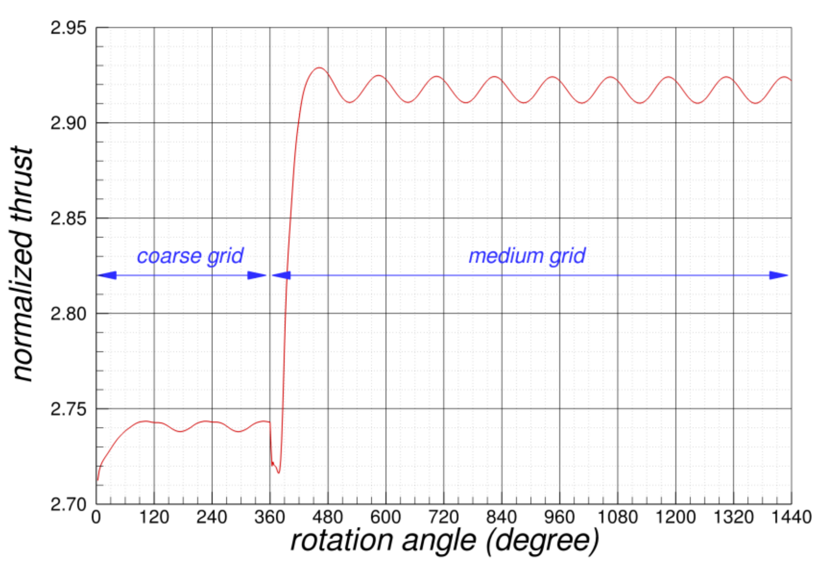
2.5D simplification of NASA Rotor-67
with circumferentially varying inflow



2. Phase-lagged boundary condition

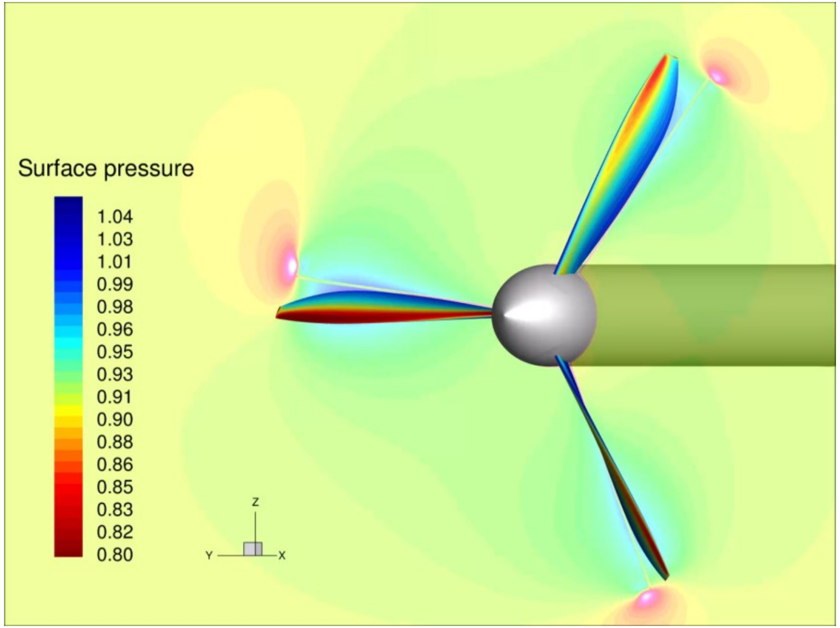


Flow (forward/primal) problem

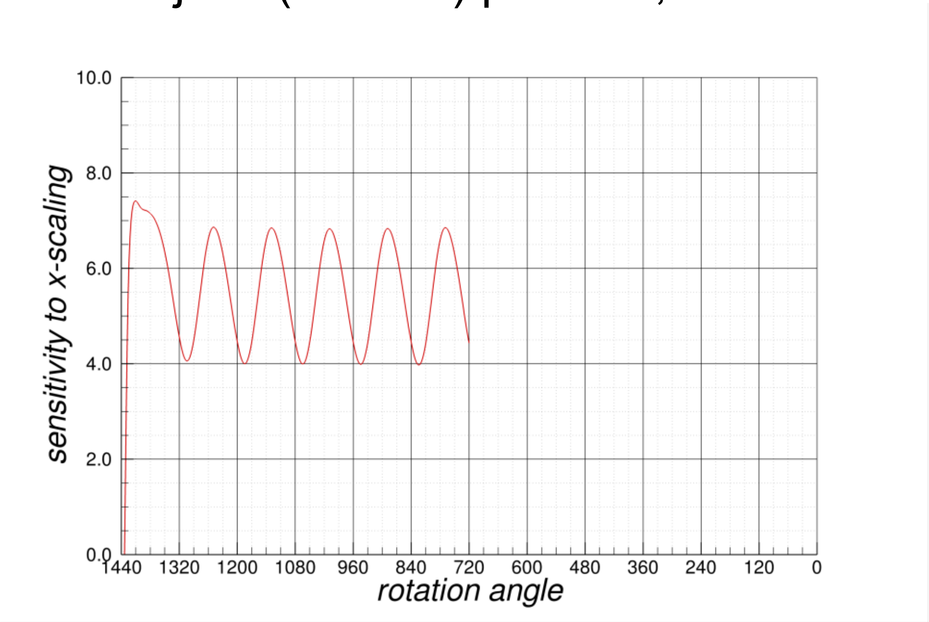


2. Phase-lagged boundary condition

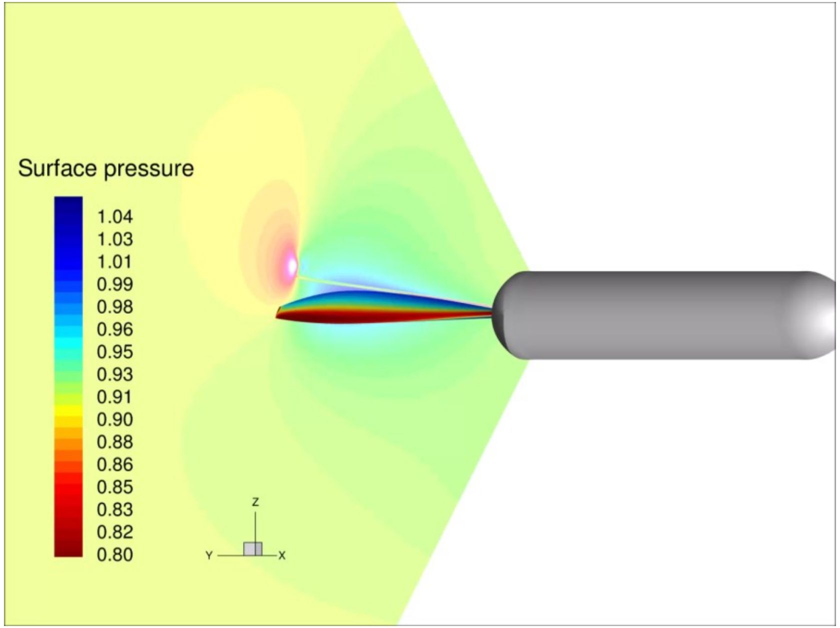
Propeller rotation is reversed



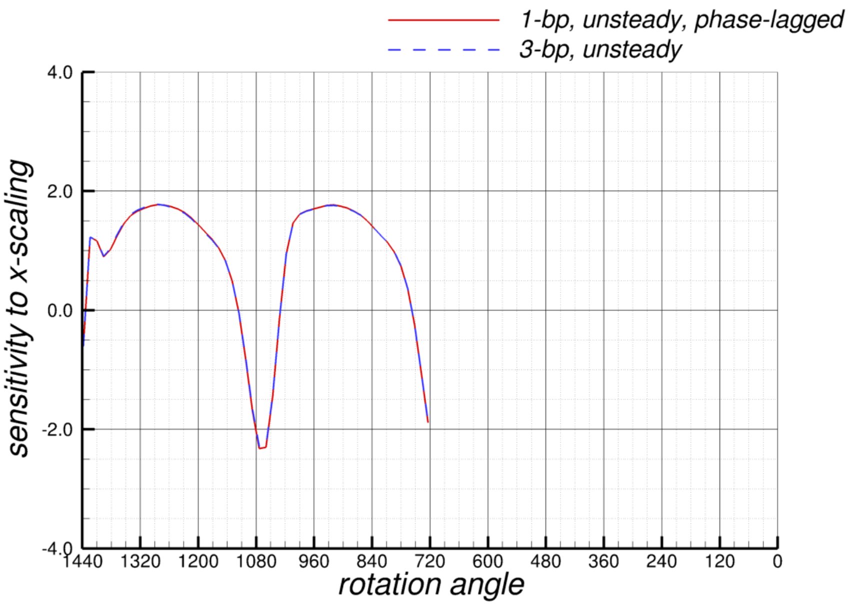
Adjoint (reverse) problem, 3-BP



2. Phase-lagged boundary condition

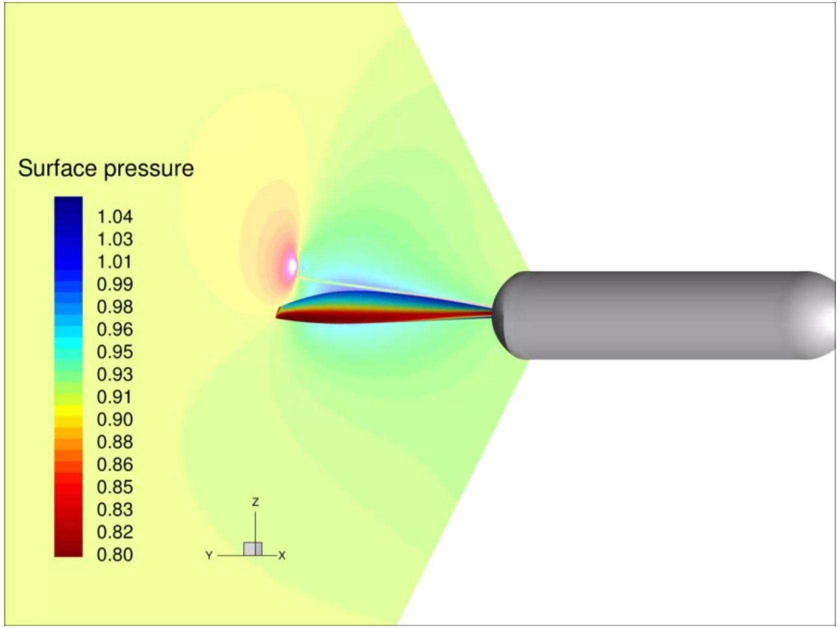


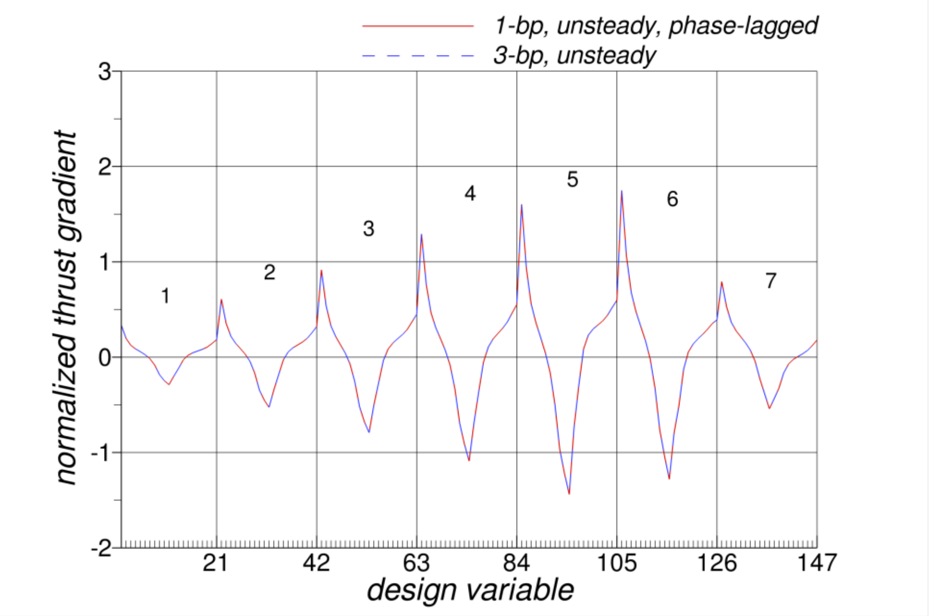
Adjoint (reverse) problem, 1-BP



2. Phase-lagged boundary condition

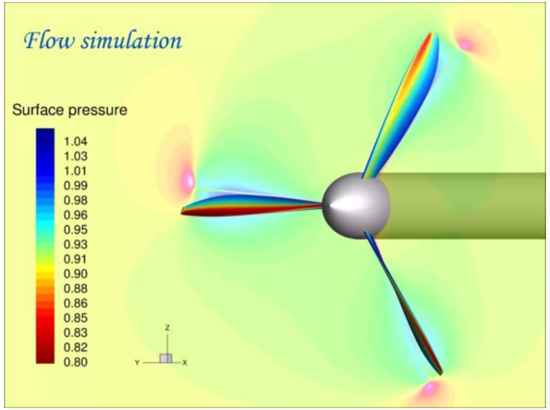
3 times less storage, I/O loads and CPU time





Conclusions

- The development of an unsteady adjoint solver has been presented.
- A sequence of verification has been conducted, utilizing test cases with increasing complexity from a simple academic to an industrially relevant test case.
- The aim of the verification is two-fold, to show that
  a) the unsteady adjoint solution procedure will lead to the correct sensitivity or gradient of the aerodynamic and acoustic functionals,
  b) a significant performance gain proportional to the number of blades can be achieved by means of a phase-lagged boundary condition.
- a sound foundation has been achieved to allow a correct and affordable aeroacoustic propeller design optimization that need to be performed in future work, involving unsteady interactional flows.



Thank you!

MADELEINE

Acknowledgment

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