Maximum Thrust Studies Of An Isolated Rotor With CFD

Turbulence Modelling And Grid Sensitivities

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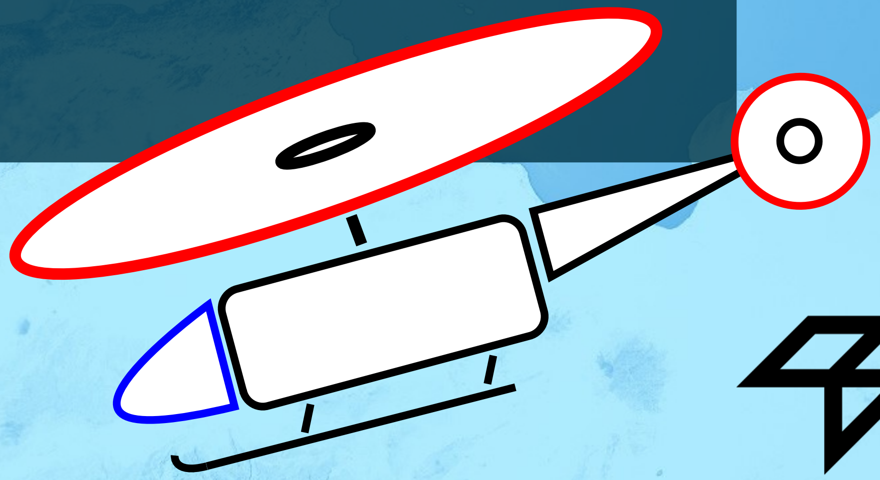


DLR

Motivation

- A goal of the helicopter department at the Institute of Aerodynamics and Flow Technology is to obtain the ability to compute the McHugh[1] stall boundary for any given rotor
- The department of helicopters at the DLR Institute of Aerodynamics and Flow Technology is determined to investigate the McHugh stall boundary numerical
- This study aims to find the boundary in hover in dependency of different numerical parameters – also inspired by Berend van der Wall's studies[2] with a comprehensive code

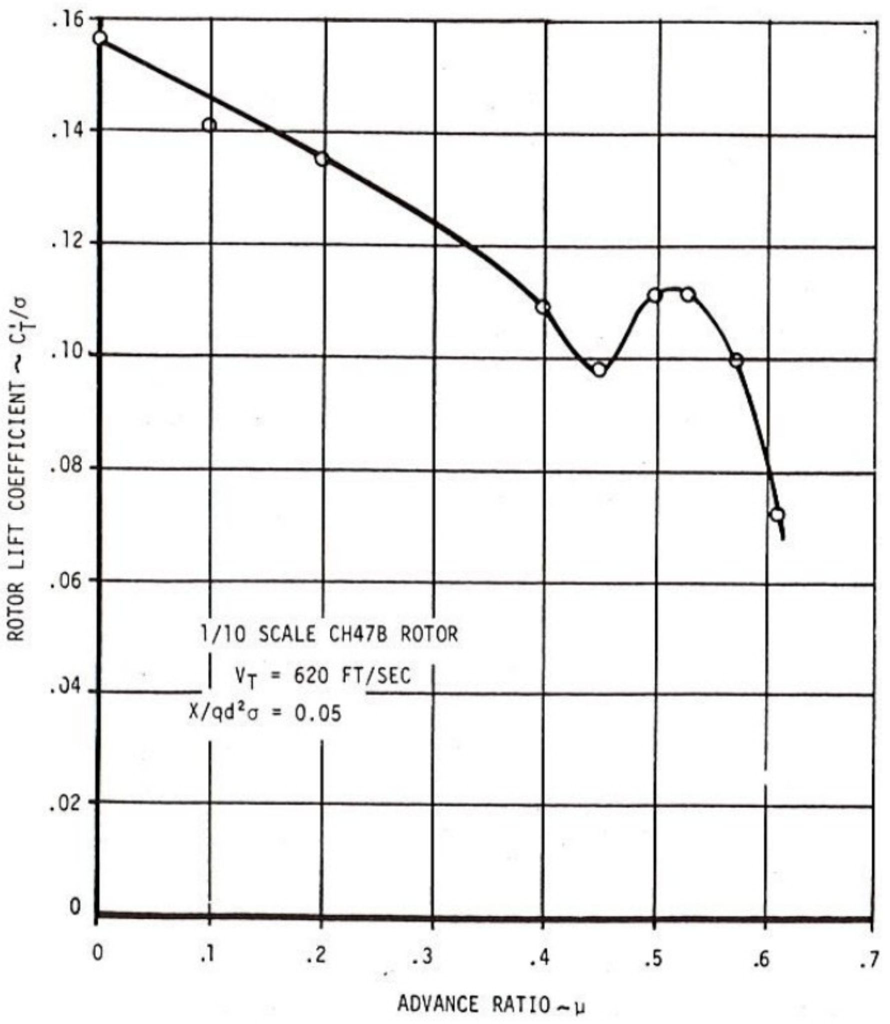


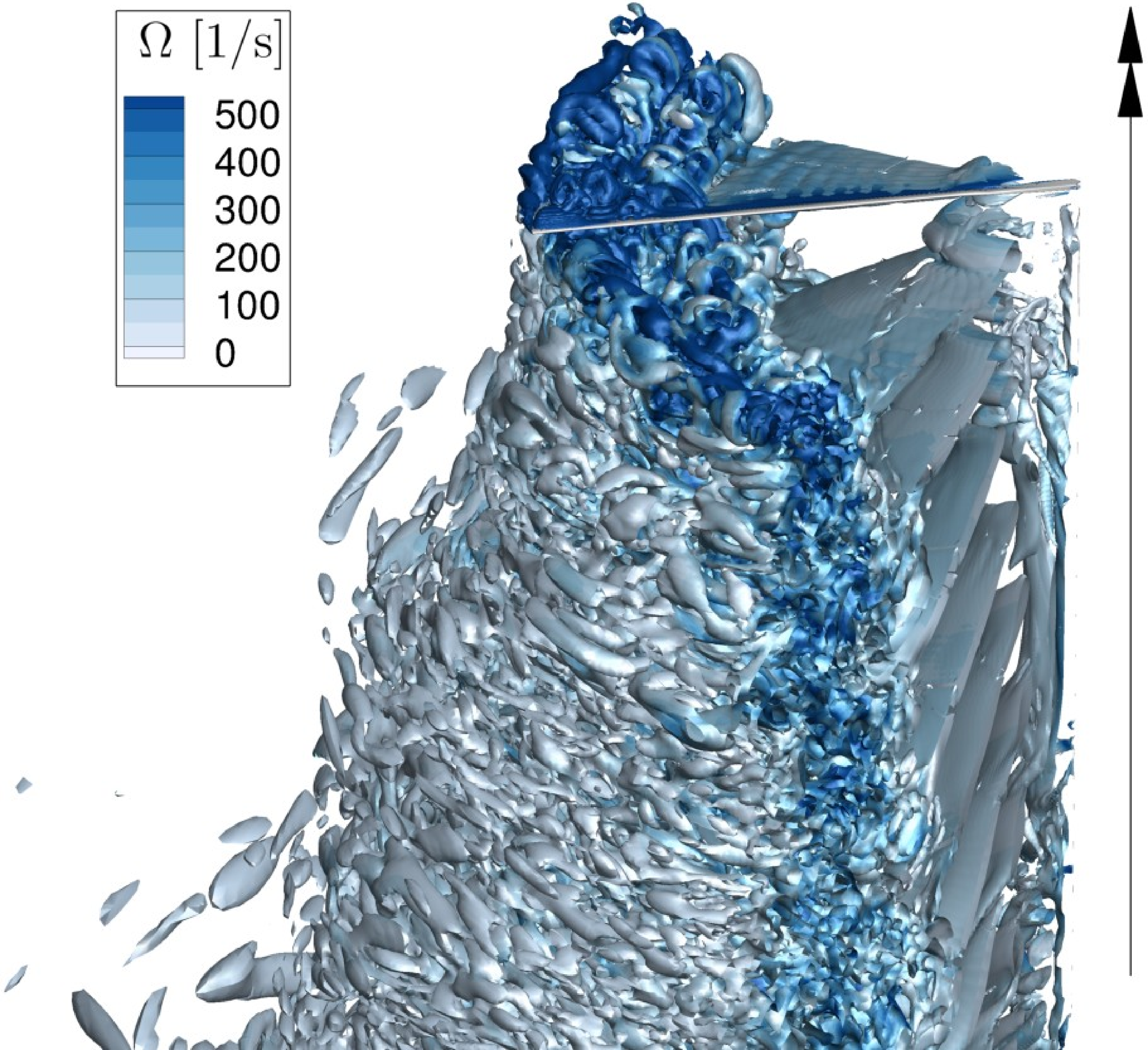
Figure 7. Maximum Lift Limit

[1] *What are the Lift and Propulsive Force Limits at High Speed for the Conventional Rotor*, F. J. McHugh, 34th Annual National Forum of the American Helicopter Society, Washington, D.C., May 1978

[2] *Impact of Rotor Inflow Modeling on Maximum Thrust, and Beyond, of an Isolated Rotor in Hover*, B. G. van der Wall, 50st European Rotorcraft Forum, Marseille, France, Sept 2024

Overview

- Intro
- Methodology
- Results
  - Temporal Accuracy
  - Spatial Accuracy
  - Grid Types
  - Turbulence Models
- Summary



Introduction

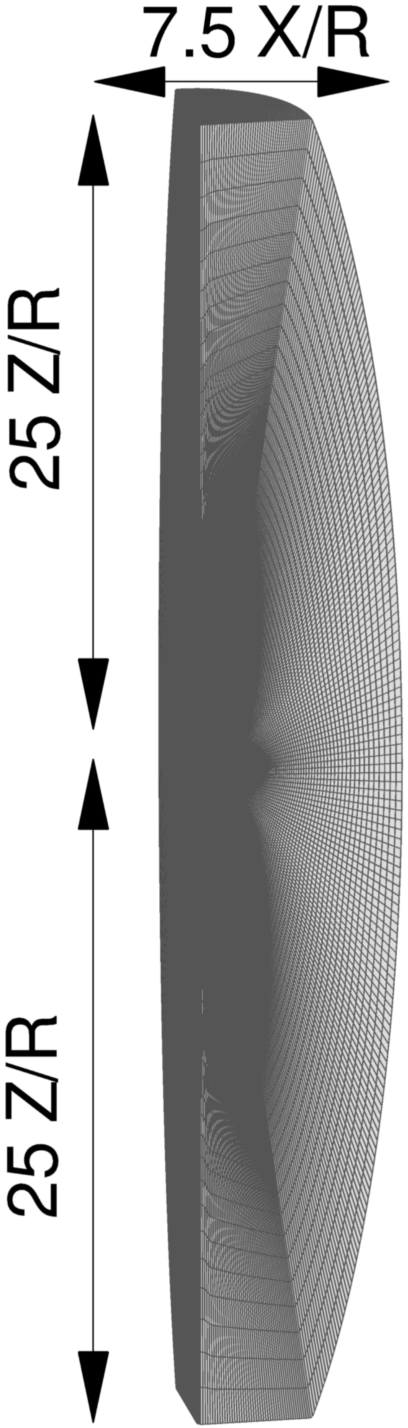
- A lot of research on dynamic stall exists, a good summary is given by Smith et al. [1]
- A lot of research on hover simulations is done in the AIAA hover prediction workshop, but also many American institutions, Chaderjian[2]
- In both cases, it seems that a high spatial resolution (many grid points and higher order schemes) with a reasonable temporal resolution (BDF2 at $\Delta\psi \sim 0.01 \ldots 1.0°$) are the way to go. On the turbulence modeling side, SA and SST are the two popular choices enhanced with DDES, sometimes enhanced with vortex/curvature corrections and/or transition prediction
- However, not much research is done on maximum thrust in hover → we will attempt this here, but focus on the aerodynamic and numerical aspects thus we will neglect elastics and blade dynamics!

[1] M. J. Smith, A. D. Gardner, R. Jain, D. Peters, and F. Richez, “Rotating Wing Dynamic Stall: State of the Art and Future Directions,” 76th Annual Forum of the Vertical Flight Society, 2020.

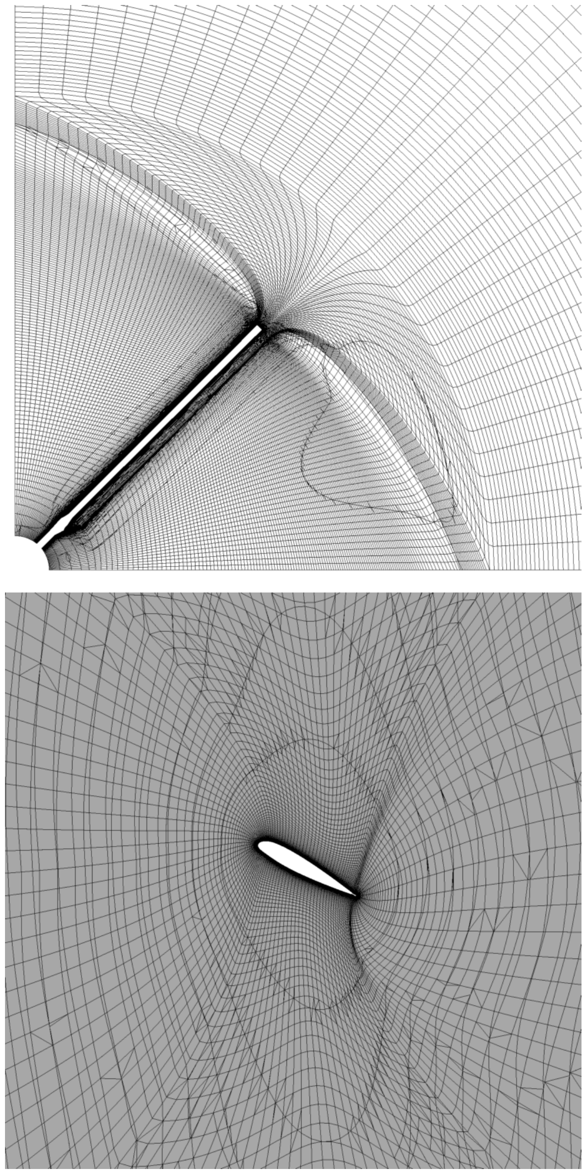
[2] N. M. Chaderjian, “A Quantitative Approach for the Accurate CFD Simulation of Hover in Turbulent Flow,” Journal of the American Helicopter Society, Vol. 68, (4), 2023, pp. 42009–42028

Methodology

- DLR’s legacy flow solver FLOWer is employed with the following settings:
  - SLAU2n convective flux scheme
  - 2nd to 4th order MUSCL scheme (FCMT with van Albada limiter)
  - SA 2012 and Menter SST 2003 turbulence models
  - with either Dacles-Mariani et al. or Dol et al. vortex correction on production terms
  - With and without DDES extension and empirical transition prediction
  - BDF 0,1,2,2opt order dual time stepping with LU-SGS for the pseudo-time

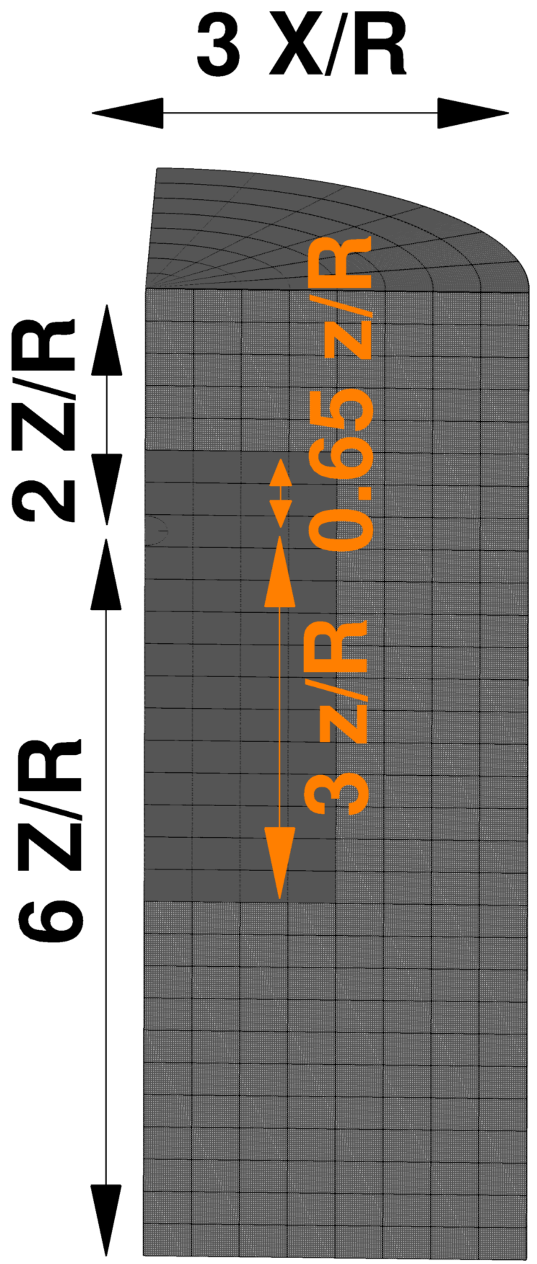


Monocoque grids

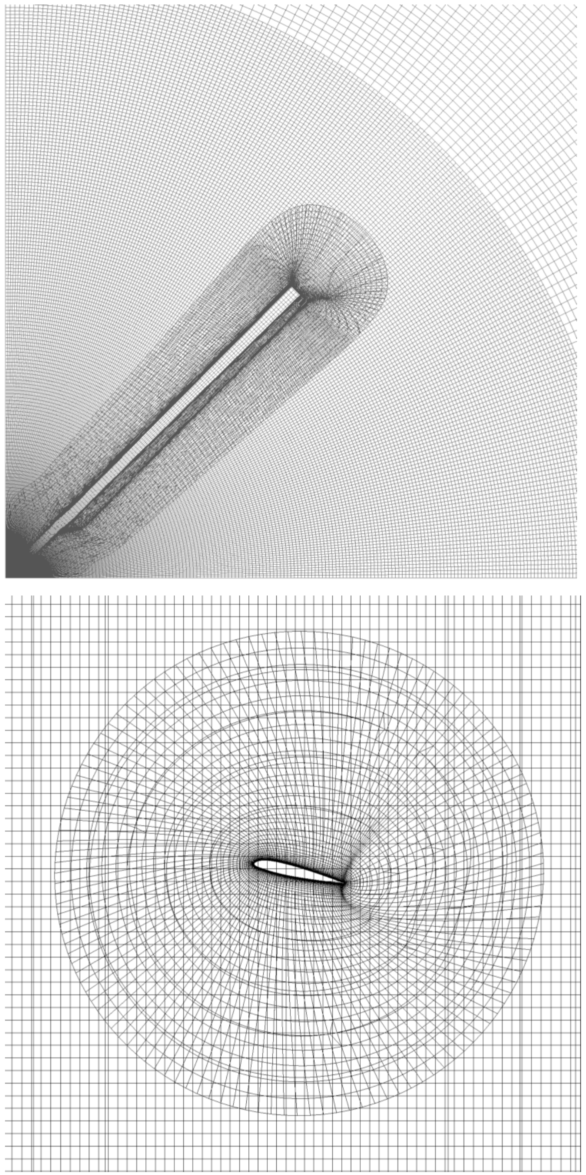


Methodology

- Utilization of in-house grid generator G³ based on transfinite interpolation and mid-point smoothers
  - Two grid types: monocoque and Chimera, later exploits hanging grid nodes
  - Multiple grid sizes investigated
  - In both cases, only ¼ rotor simulated and periodic conditions exploited
  - Grid numbers will be specifically mentioned in the plots



Chimera grids



More details in the paper!

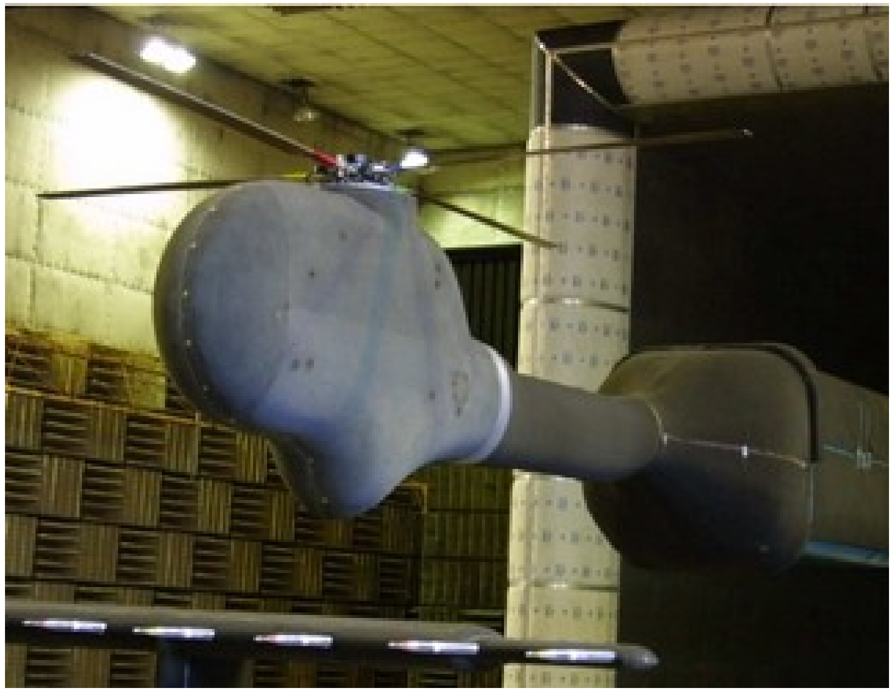
Grid type	Monocoque	Chimera
chordwise	128	
radial	128	
BL[1]	≈ 30	
normal	128	64
$\Delta z/c_{ref}$	0.37	0.14
$\Delta\psi R/c_{ref}$	0.45	0.19
blade	2.1e6	1.0e6
background	0.7e6	2.1e7
total	2.8e6	2.2e7

Test case

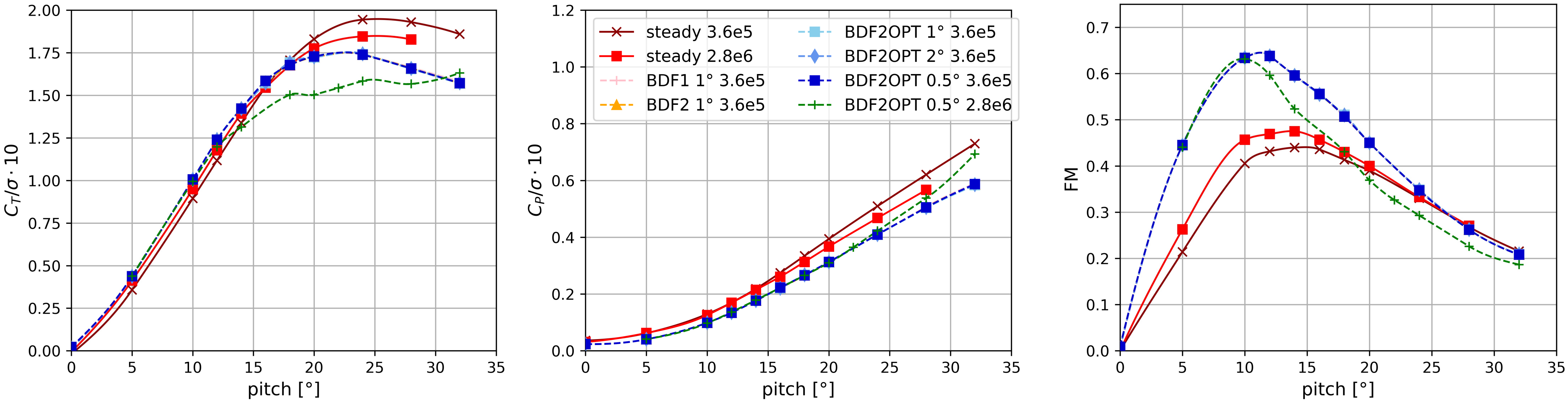
HART-II	
R	2 m
c_{ref}	0.121 m
twist	$-8^o/R$
airfoil	NACA 23012 with tab
M_{tip}	0.64
Re_{tip}	1.8e6
M_∞	0.0

- The considered rotor is the HART II rotor rigidly modeled w/o precone
- Isolated simulation, no rotor head, no fuselage, no wind tunnel
- Data averaged over 1 rev shown, 30 revs run
- Results are split into the following sections
  - Temporal accuracy study
  - Spatial accuracy study

    → both on monocoque grids only
  - Grid type study
  - Turbulence models
    → Chimera grids only

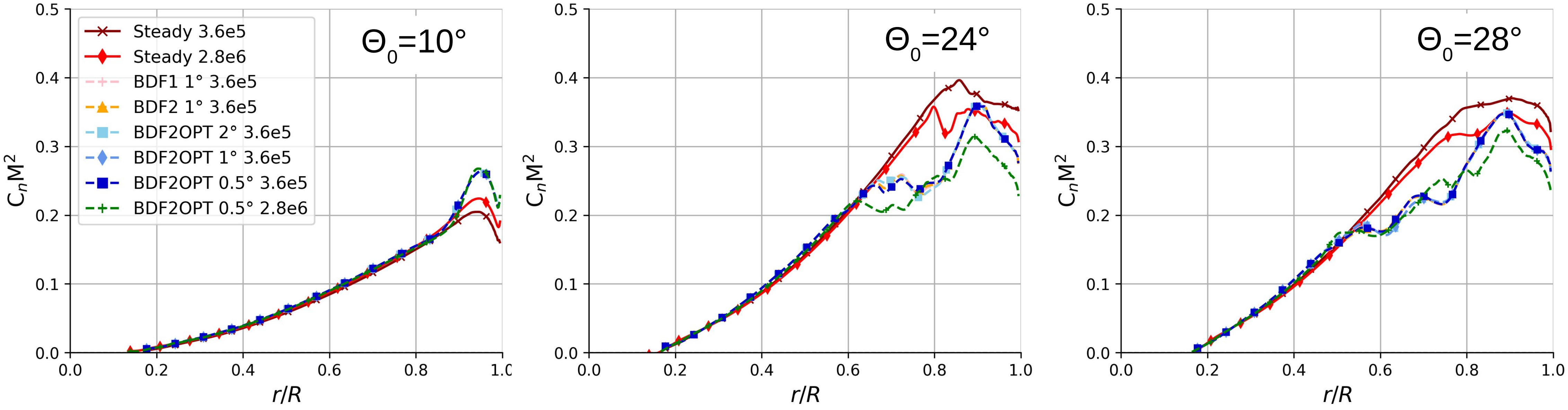


Temporal Accuracy



- Despite being the temporal accuracy study, the inter-dependency with the spatial resolution is studied. Here, the 2nd order reconstruction is used.
- In the linear thrust range, the impact of the resolution seems negligible, but in terms of torque albeit FM, the steady simulations show high drag results
- The finer grids lowered the maximum thrust for steady and unsteady cases
- The unsteady results are grouped very close to each

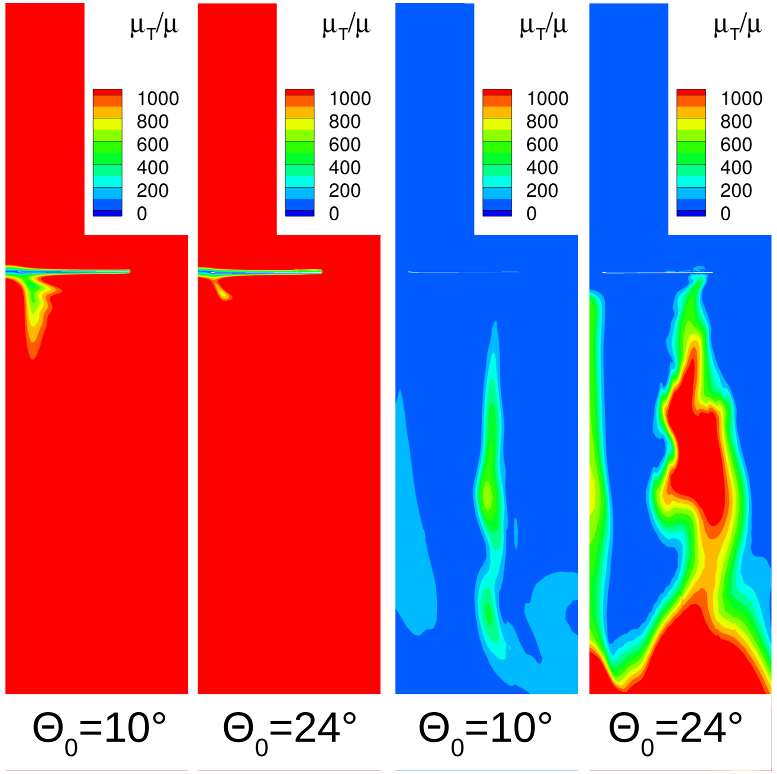
Temporal Accuracy

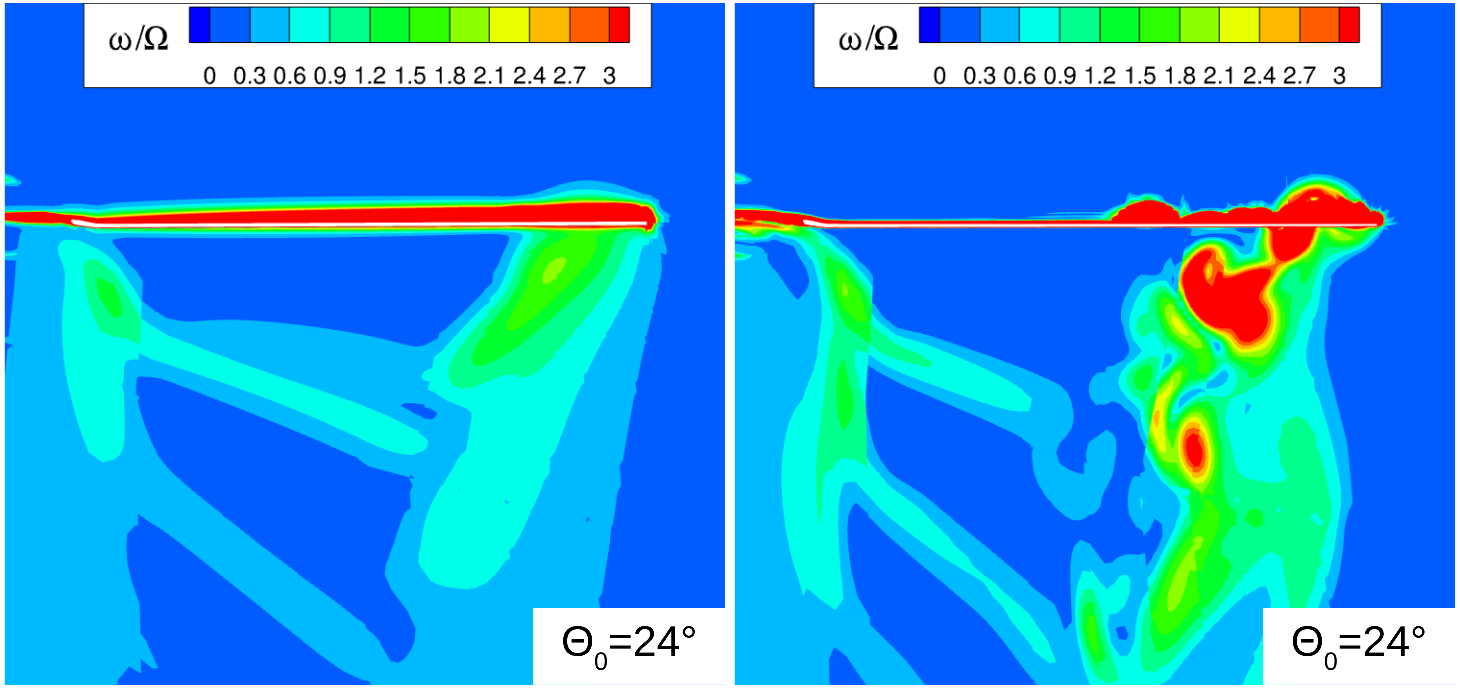


- Here, only the normal force plots are shown, but in the paper, the tangential force as well the pitching moment are plotted, too.
- As with the integral load plots, the linear range is very close to each other, but the vortex is very differently perceived for the steady simulations, whereas the unsteady simulations are close to each other
- The cost differences between BDF1 to BDF2OPT is more or less the same. Smaller time steps reduce the required inner iterations in a similar order as more time steps become necessary

Temporal Accuracy

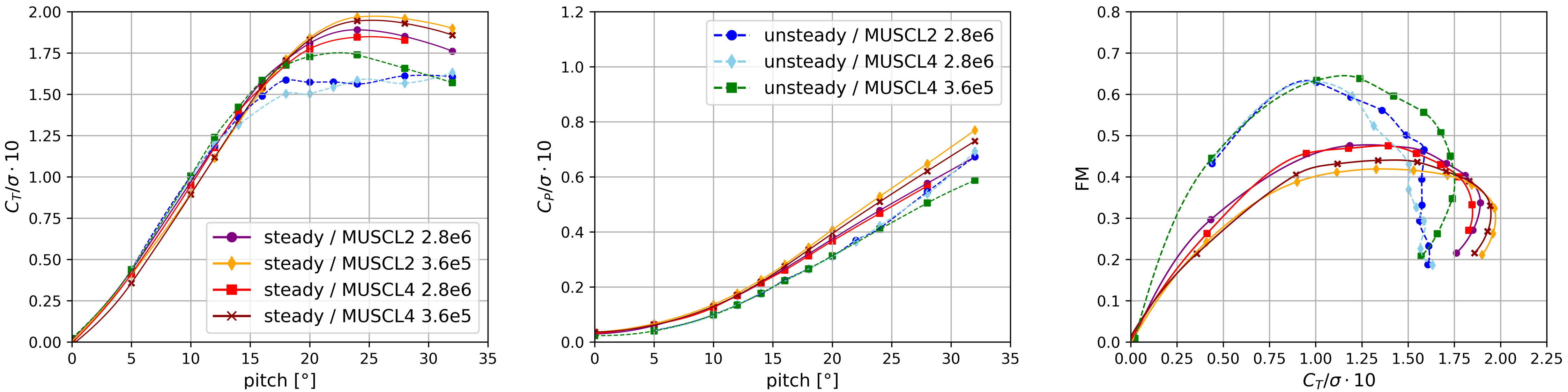
2.8e6 monocoque grid





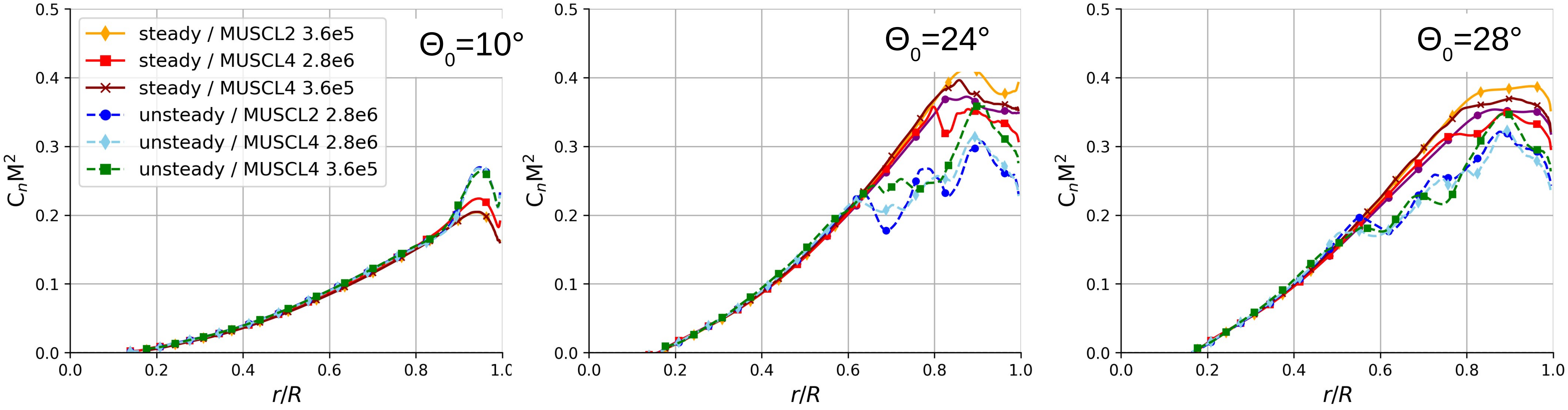
- The reason why steady simulations suffer from high drag and little vortex preservation is that the SA model "floods" the flow field with eddy viscosity since in its standard form the production is not suppressed while the destruction term tends to zero far away from the geometry → see concurrent DLR paper by Hong et al. at ERF

Spatial Accuracy



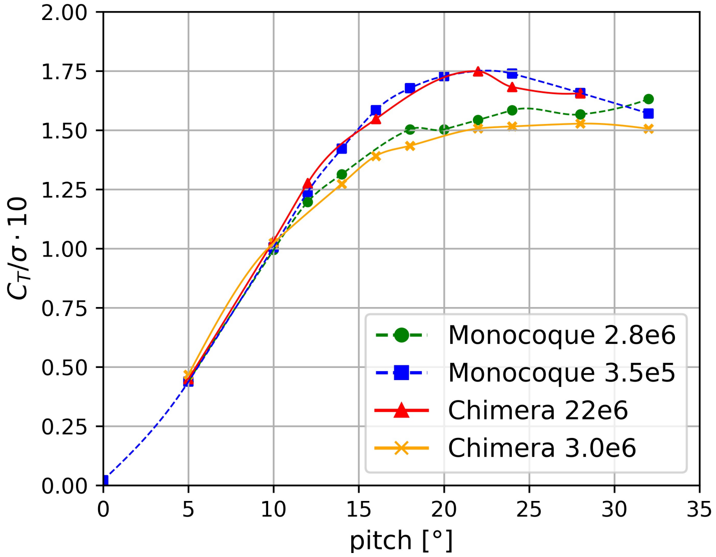
- Similarly to the previous study, the inter-dependency with the temporal resolution is investigated. The unsteady simulations are here run with BDF2OPT and Δψ=0.5°
- From this initial glance, one can see that the number of grid points has a higher impact than changing the spatial order
- The added computational cost, however, is also small (~10-15%) - 5% more per iteration, 10% more inner-iterations for convergence

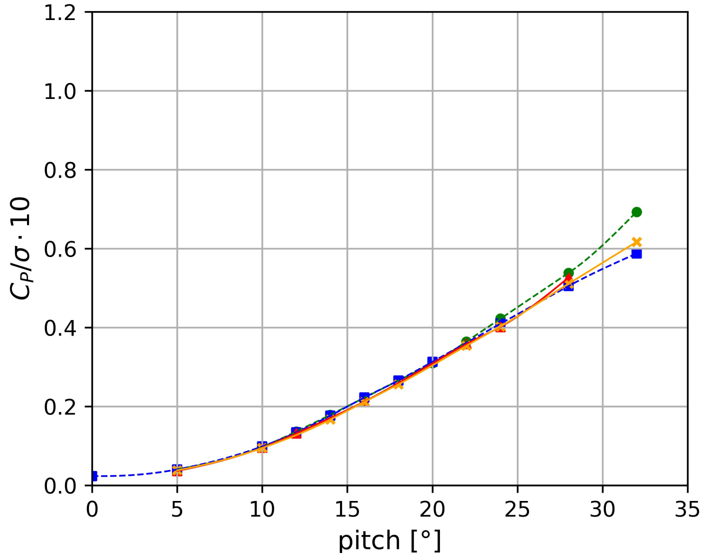
Spatial Accuracy

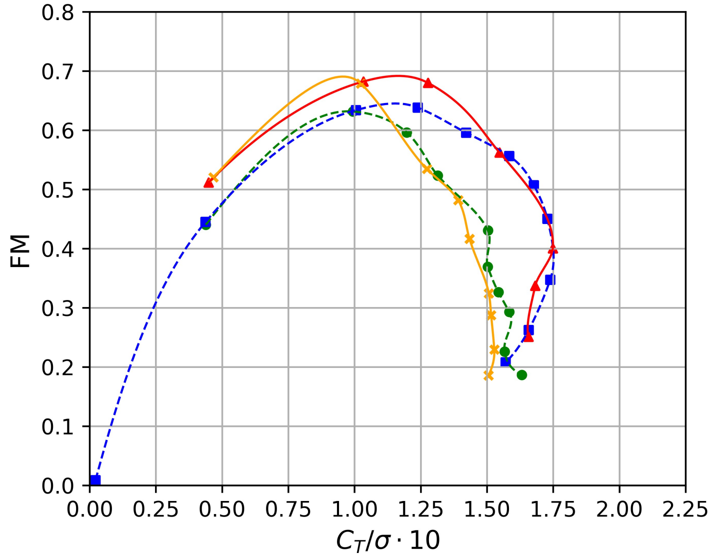


- The difference between steady and unsteady is larger than the impact of the spatial scheme.
- Despite the eddy viscosity flooding for the steady cases, the sharper vortex resolution is visible for both cases at the lower thrust
- Further tests are now carried out with BDF2OPT and 4th order MUSCL

Grid types

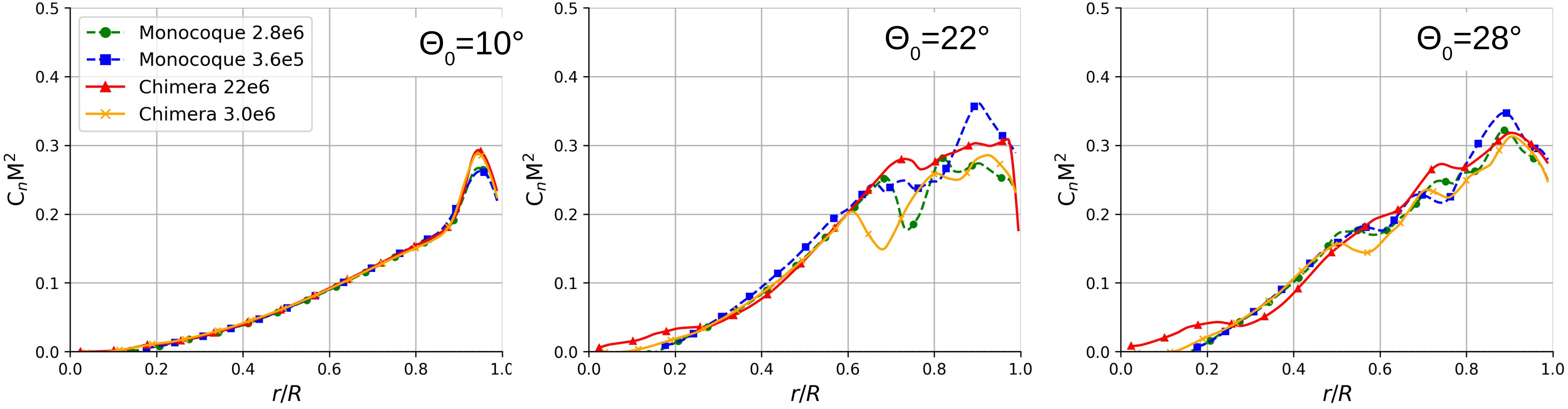






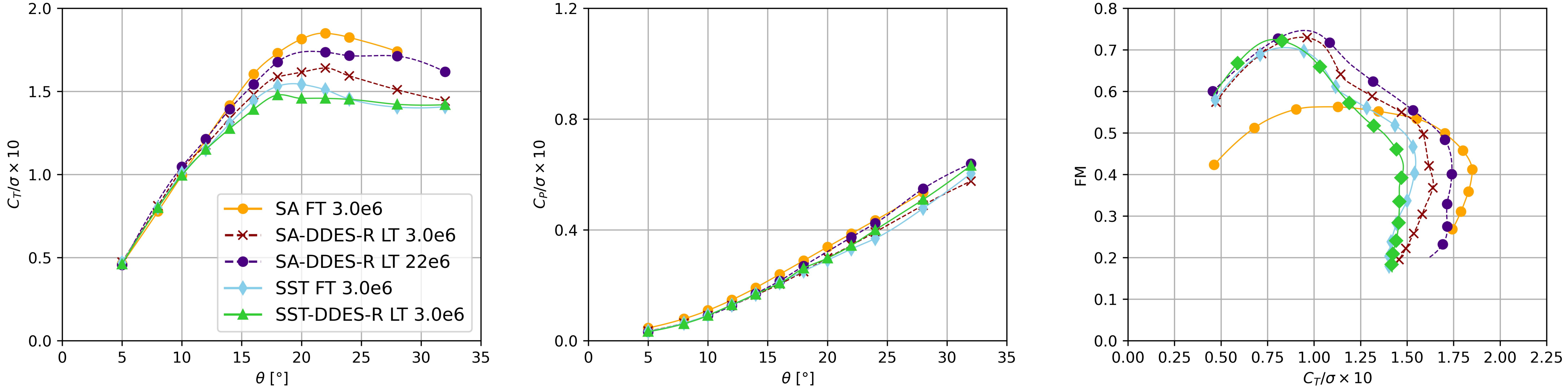
- BDF2OPT with 4th order MUSCL applied for both, SA turbulence model
- Interesting results – the coarse monocoque simulation aligns with the finer Chimera setup, whereas the fine monocoque simulation aligns well with the coarse Chimera simulation

Grid types



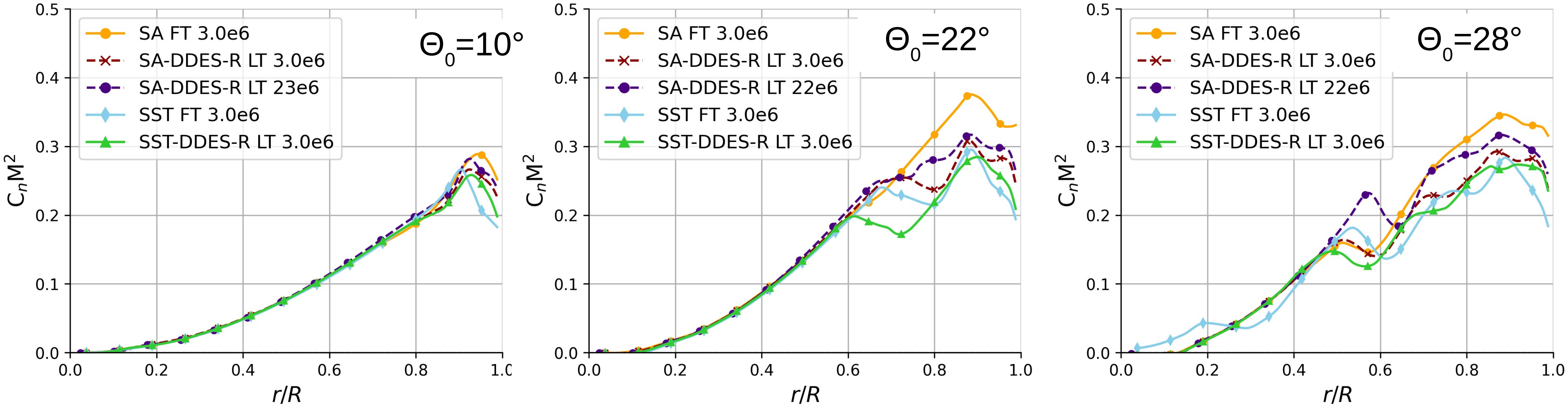
- The overset cases show a stronger tip vortex in the normal loads for the Θ_0=10° case
- At roughly maximum thrust, the normal force appears relatively chaotic, while at the post stall angle, a sin-wave like distribution is observed
- The MUSCL reconstruction does not consider irregular cells. Therefore it benefits from the more regular cells in the background grid for the Chimera cases. However, a minimum of points is required for a reasonable overlap, and for efficient simulations, monocoque may be more suited, whereas above ~ 3e6 points Chimera is more feasible

Turbulence Models SA vs SST



- Selected simulations of SA and SST are compared
- The plain model variants show significantly different results
- The SA-DDES-R LT and SST-DDES-R LT model variants are closer together on the same grid, and differences are little in the linear thrust range, but for maximum thrust show still a greater difference
- This difference is of similar magnitude as the change from the coarse to the fine grid

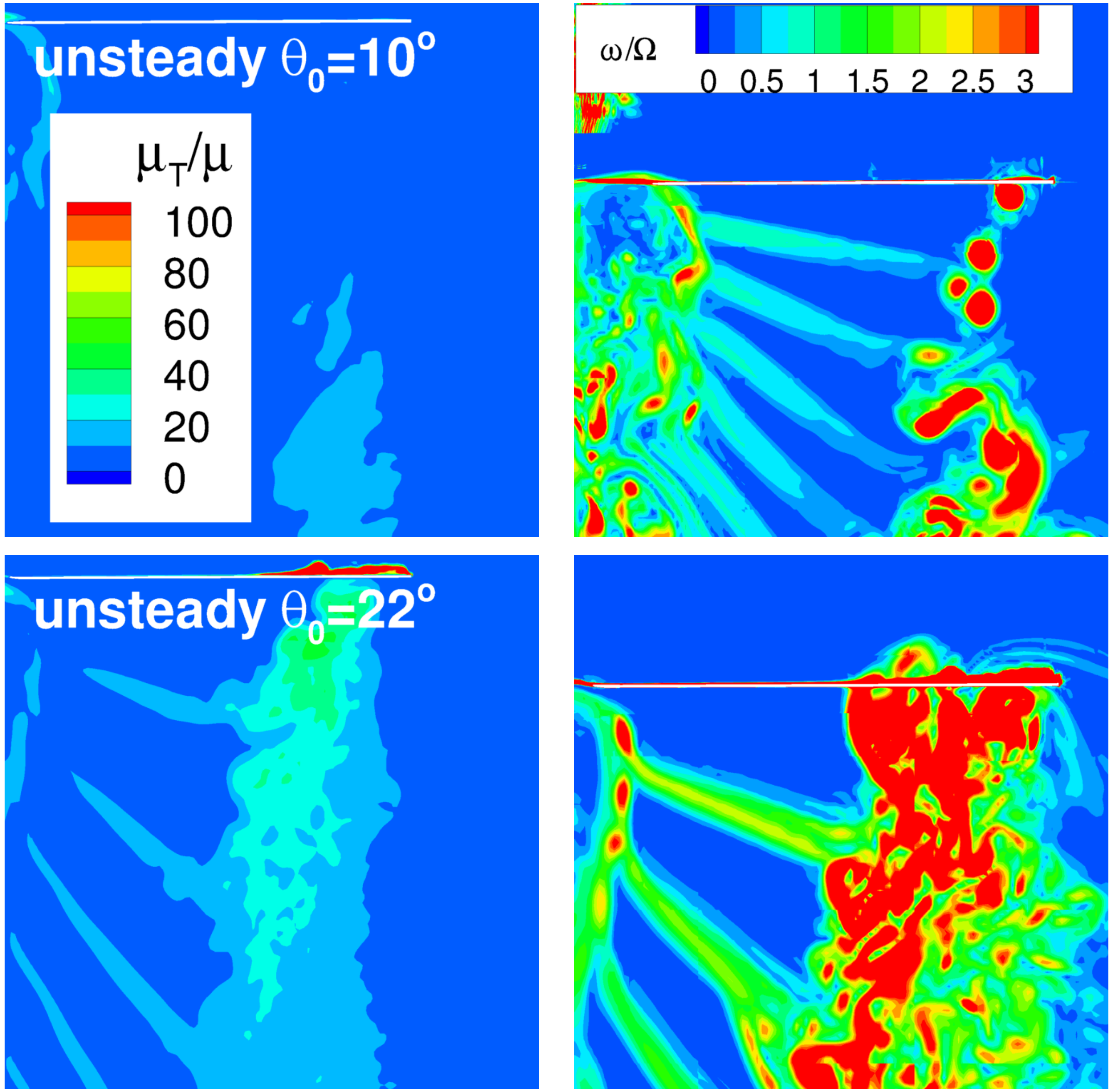
Turbulence Models SA vs SST



- At Θ_0=10°, the SA-DDES-R LT and SST-DDES-R LT models show very similar results. The plain SA model seems to be the overall outlier due to increased eddy viscosity production
- In general, SA model shows higher normal forces (and thrust) than the SST model.
- The difference between the SA-DDES-R LT and SST-DDES-R LT model on the same grid are slightly smaller than the impact of increasing grid points (as already found for the integral values)

Vorticity and Eddy viscosity

- SA-DDES-R on the fine grid shows a strong reduction of eddy viscosity in the field.
- At the same time, the vorticity is better preserved.
- Nevertheless, at higher collective pitch angles, the eddy viscosity from the separated boundary layer is transported into the field, leading to a mixture of resolved and modeled vorticity.
- Thus, using DES for rotor flows even at moderate spatial and temporal resolutions appears to quiet reasonable.



Conclusions

- Unsteady simulations are highly recommend, however, the temporal accuracy has shown little impact. It was generally observed that smaller time steps converge better and thus it should be chosen to minimize the overall number of required inner iterations.
- The monocoque grid is an efficient setup, but with more grid points the Chimera/Overset approach becomes more viable as the more even background grid allows to better preserve accuracy at (simple) 2^{nd} order metrics.
- Spatial resolution is critical and grid points help more than higher order. However, for the structured grid process, the cost from going from 2^{nd} to 4^{th} order reconstruction is ~ 5% more computational resources per iteration and a 10-20% loss of convergence speed.
- The SA model may lead to ‘eddy viscosity flooding’ due to an unbounded production term and a diminishing destruction term away from the wall.
- The SST model did not show such issues, but generally converged slower by about 30-50% with respect to SA simulations.
- Independent of the turbulence model, DDES and R corrections should be applied in either case as it increases accuracy through the removal of unnecessary eddy viscosity.

Conclusions cont‘d

- Laminar-turbulent transition prediction had little impact on maximum thrust due to the suction side being fully turbulent either way. The maximum Figure of Merit was more impacted by this.

- The rotor stall was observed here around Θ_0=20-24° with the c_T/σ ~ 0.14 – 0.19. The rotor stalled outboard first and at maximum thrust, roughly all sections past r/R>0.6 were stalled, while the inboard stations still produced thrust.

  → finer grids and stronger solvers will always be recommend for further endeavors into this research. A question is how important the secondary vortices are for the correct prediction of integral values, but also sectional forces and moments.

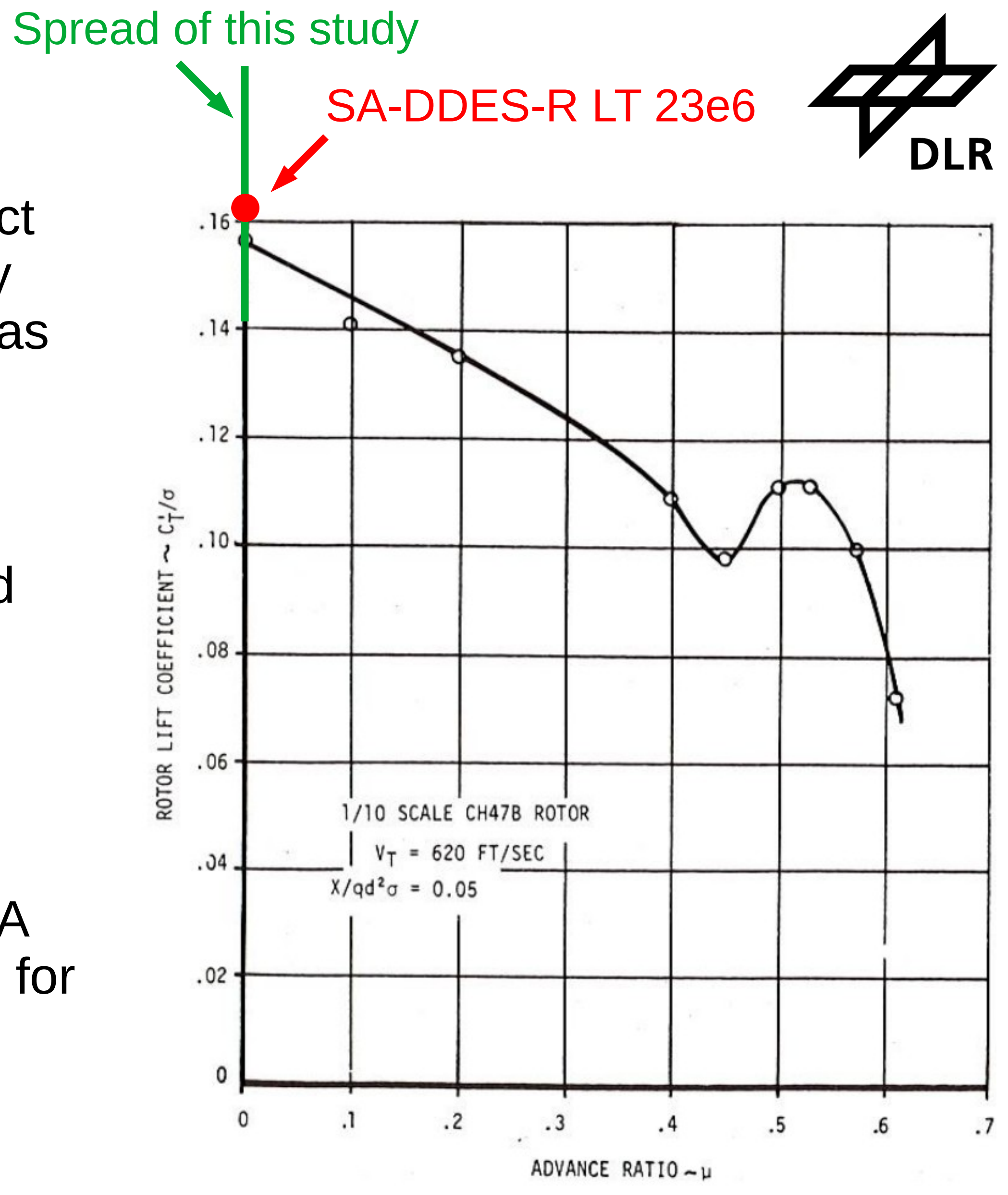


Figure 7. Maximum Lift Limit