Vortex-induced stall on an actively twisted highly loaded model rotor blade

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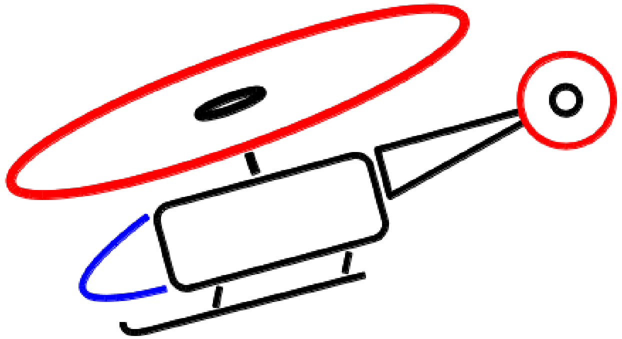

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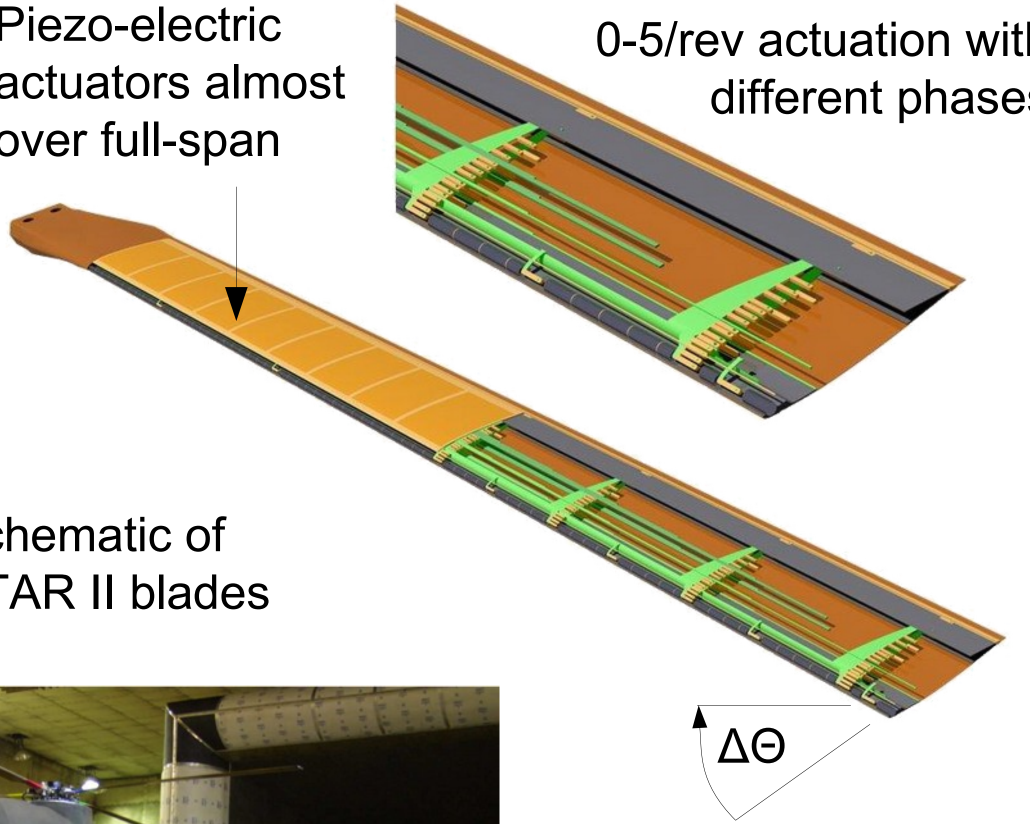
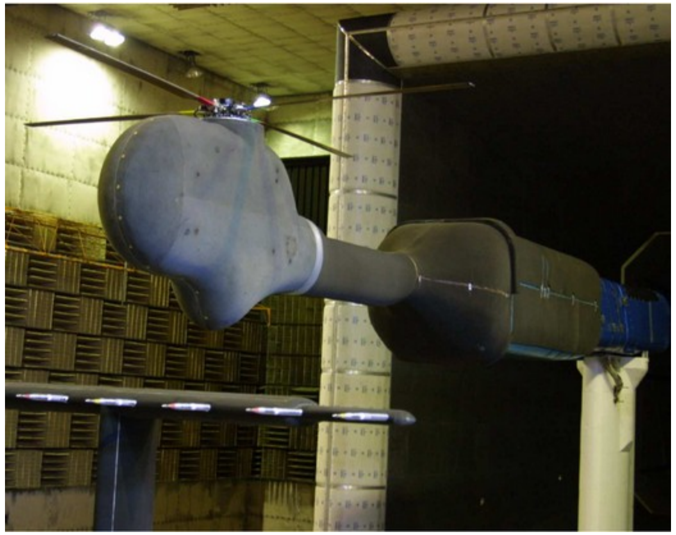
Motivation & Introduction

- Helicopter rotor blade sections operate in very different flow conditions
- The difficulty is that a passively designed rotor blade is always a trade-off of the various flow & flight conditions
- Many blade control devices have been studied, in the STAR II project shown here, actively twisted blades are investigated
- STAR II is a consortium of 8 research centers (7 participated in the vortex induced stall, high load activity)
- Test matrix has been simulated before the wind tunnel test, this presentation is about the vortex-induced stall condition (half RPM to stay within testing limitations)



Schematic of STAR II blades



STAR II will be tested like HART II blade in DNW LLF

Overview

- Methodology
- Simulation results
  - Baseline thrust sweep
  - Actuation sweeps
- Summary

DLR-CA
DLR-CFD
JAXA-CFD
KARI-CFD
KU-CA
ONERA-CA
UofG-CFD
US-CA

Methodology

- All results are fluid-structural coupled
- Two major groups:
  - Comprehensive analysis (CA) codes
  - CFD/CA coupled analysis
- CA codes use vortex wake models
- CFD codes similar order in their resolution

→ some noticeable differences in the approaches

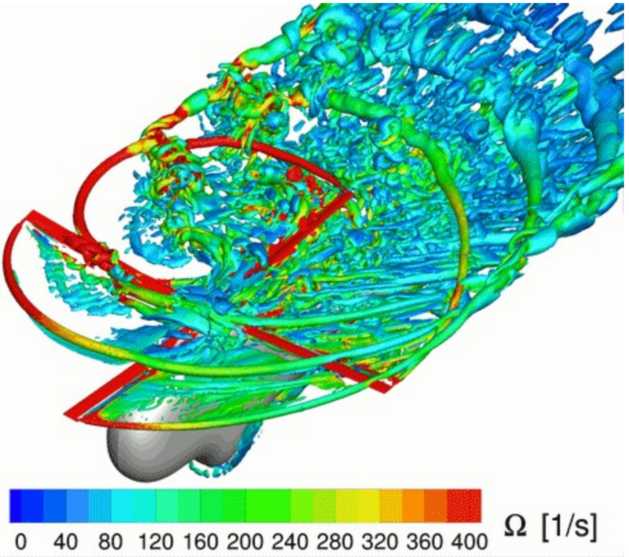
Comprehensive codes

	DLR-CA	KU-CA	ONERA-CA	US-CA
box	no	no	no	no
fuselage	yes	no	no	no
init. tip core	0.033	0.5	0.3	0.8
blade elements	20	16	25	28
azimuth step size	2°	15°	5°	15°

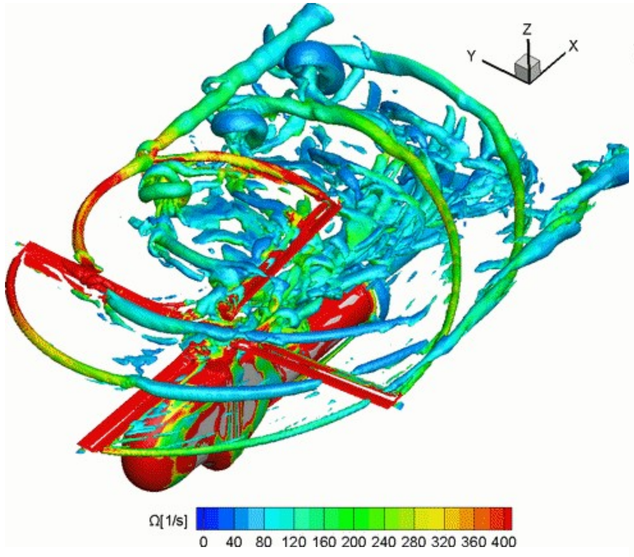
CFD coupled comprehensive codes

	DLR-CFD	JAXA-CFD	KARI-CFD	UofG-CFD
box	yes	yes	yes	no
fuselage	yes	yes	yes	no
order	4	4	2	3
turbulence	SA-DDES-R	Menter SST	SA	Menter SST
transition	empirical	γRe_θ	no	no
blade resolution	128x64x128	141x81x157	-	142x64x148
background $\Delta x/c$	14%	10%	15%	15%
total # grid pts	15 M	88 M	29 M	35 M
step	0.25°	0.1°	1.0°	0.25°

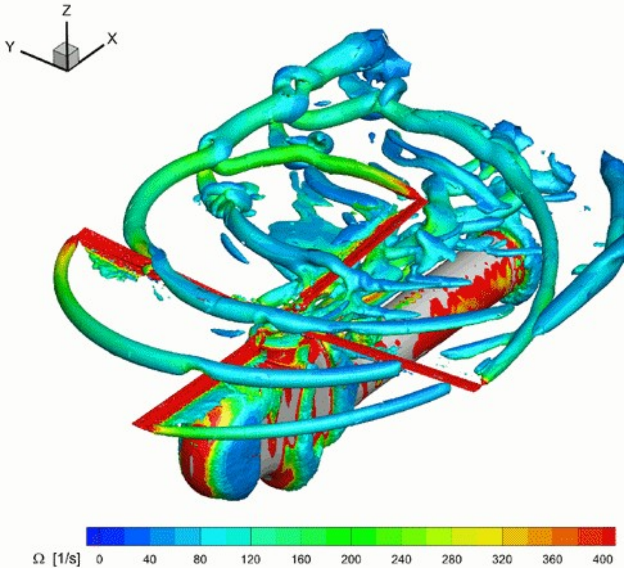
Simulation Results – Vorticity Fields @ $c_T/\sigma = 0.13$



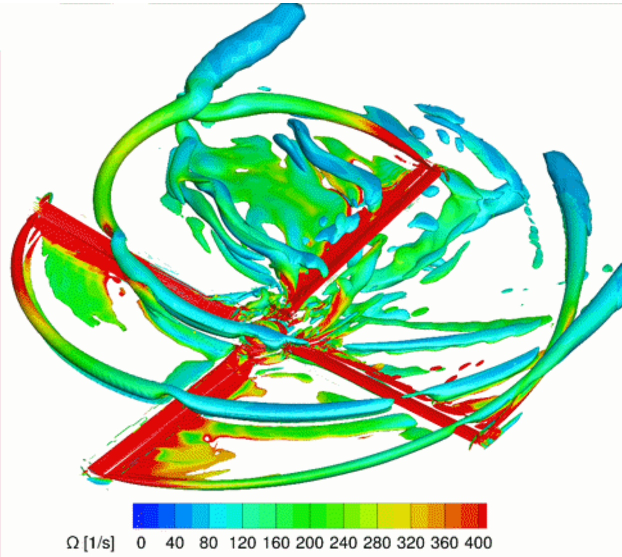
DLR-CFD
4th order, DDES,
Δx/c=14%



JAXA-CFD
4th order, URANS,
Δx/c=10%



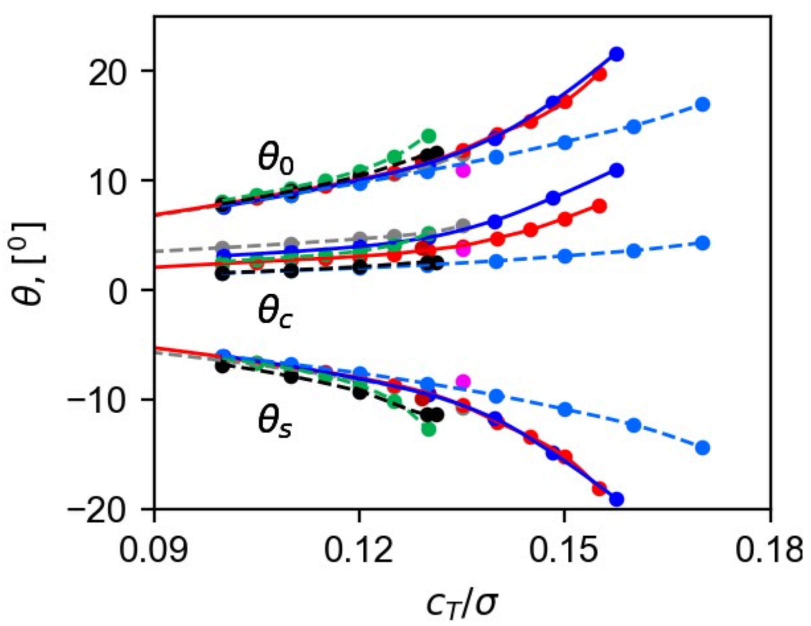
KARI-CFD
2nd order URANS,
Δx/c=15%



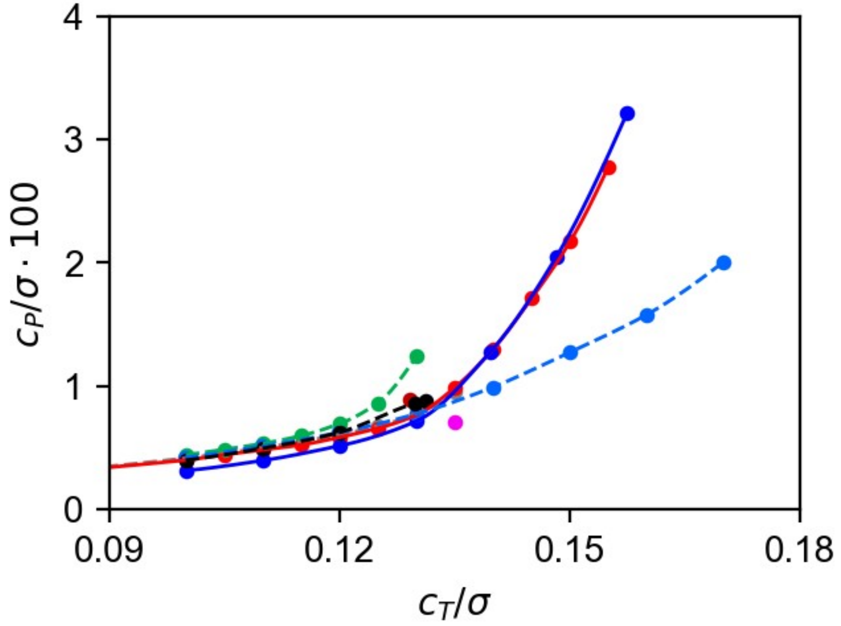
UofG-CFD
3rd order URANS,
Δx/c=15%

- General vortex trajectory very similar among partners
- Different strength of tip vortices and severity of separation captured
- 4th order simulations (with DDES) capture more secondary structures than 2nd order (URANS) simulations

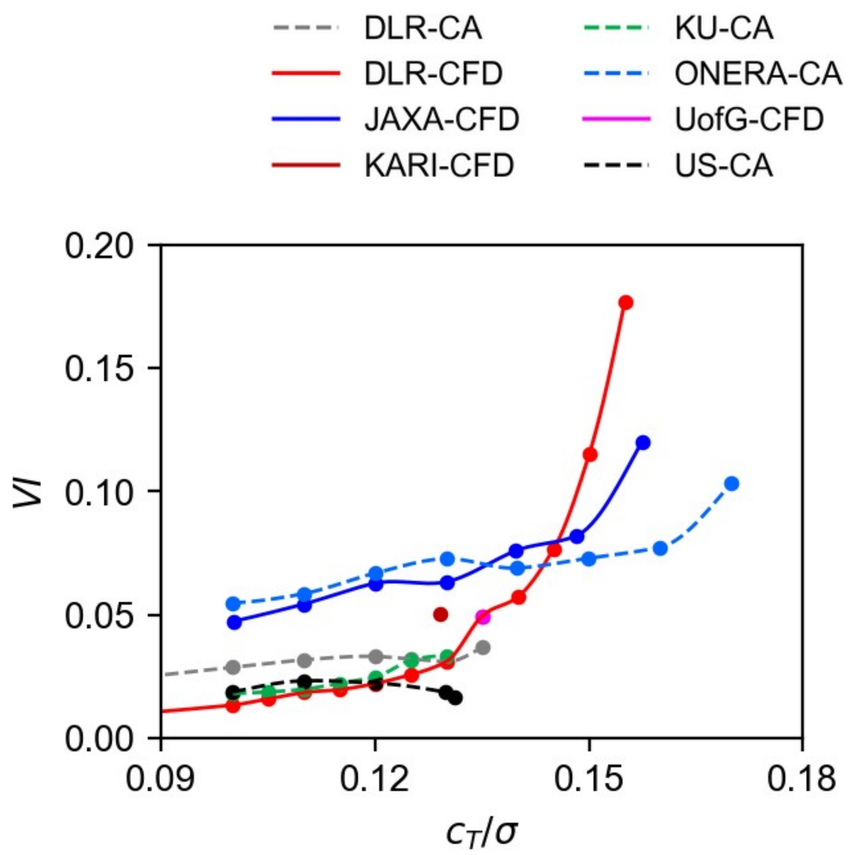
Thrust Sweep – Integral Results



Pitch control angles



Required power



Vibration Intrusion Index (VI)

- General trend captured well by all methods at lower thrusts
- Change in gradient found in most curves with the onset of dynamic stall
- Maximum trimmable thrust ranges from c_T/σ = 0.13 … 0.17
- VI metric has the greatest discrepancies with roughly the same trends

$$VI = \sum_{i=4,8} \frac{\sqrt{(0.5F_{x,i})^2 + (0.67F_{y,i})^2 + (F_{z,i})^2}}{W_0} + \sum_{i=4,8} \frac{\sqrt{(M_{x,i})^2 + (M_{y,i})^2}}{RW_0}.$$

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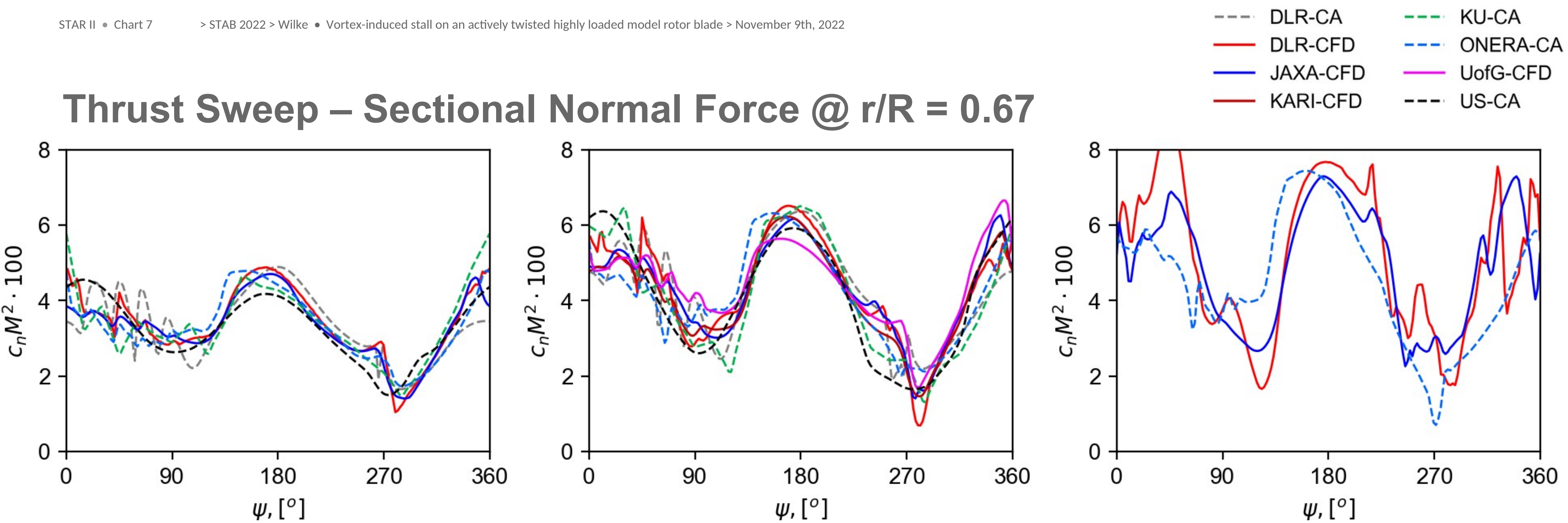
Thrust Sweep – Sectional Normal Force @ r/R = 0.67



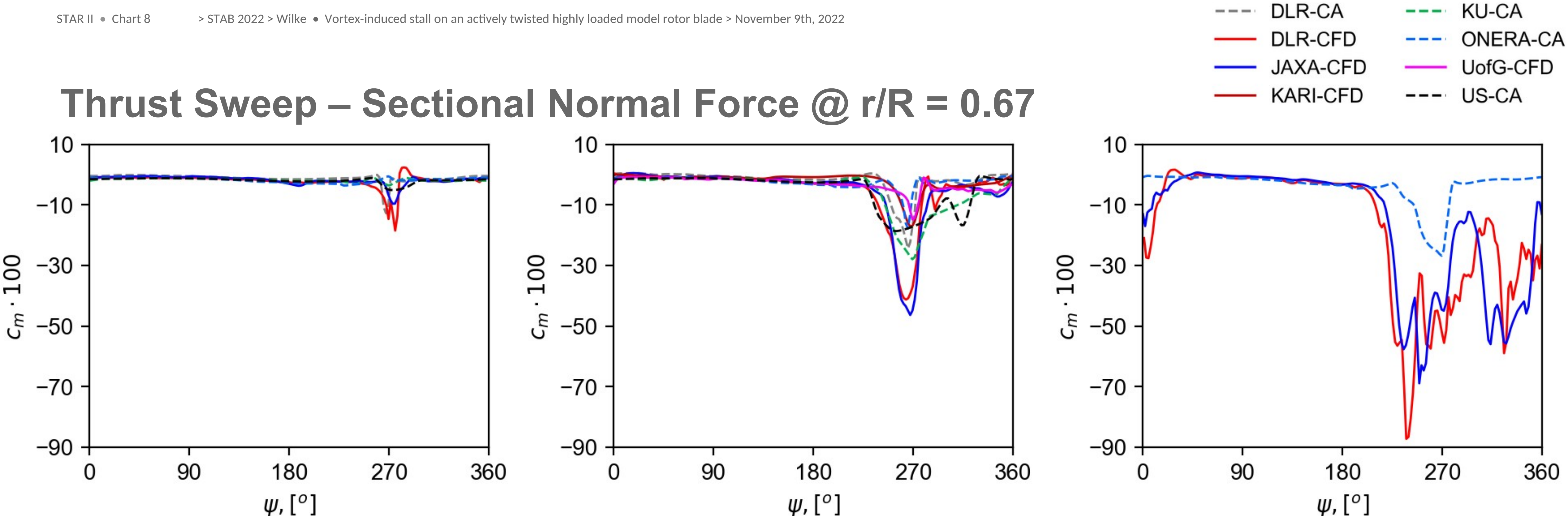
$c_T/\sigma = 0.10$

$c_T/\sigma = 0.13$

$c_T/\sigma = 0.15$

- At lower thrust, good agreement among the partners. Higher harmonic content depends on the tip vortex simulation – smaller core radii in CA or better conservation on the CFD lead to greater wiggles
- At higher thrust the discrepancies grow, at $c_T/\sigma = 0.15$, only three partners were able to trim the rotor

Thrust Sweep – Sectional Normal Force @ r/R = 0.67



c_T/σ = 0.10 c_T/σ = 0.13 c_T/σ = 0.15

- At lower thrust: no or very small onset of stall is observed on the retreating side
- DLR-CFD & JAXA-CFD capture strong dynamic stall at intermediate and high thrust.
- Higher harmonic content from the DLR-CFD (DDES) found again in the load plots, but little influence overall
- NOTE: c_m computed from $c_n M^2$ as unique inflow cannot be determined in CFD

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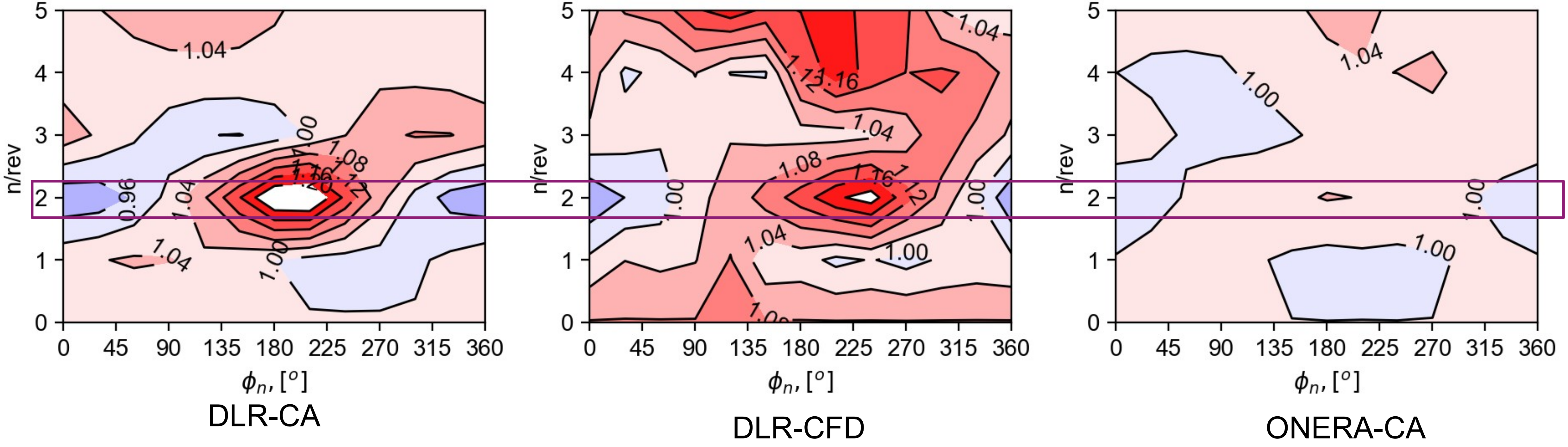
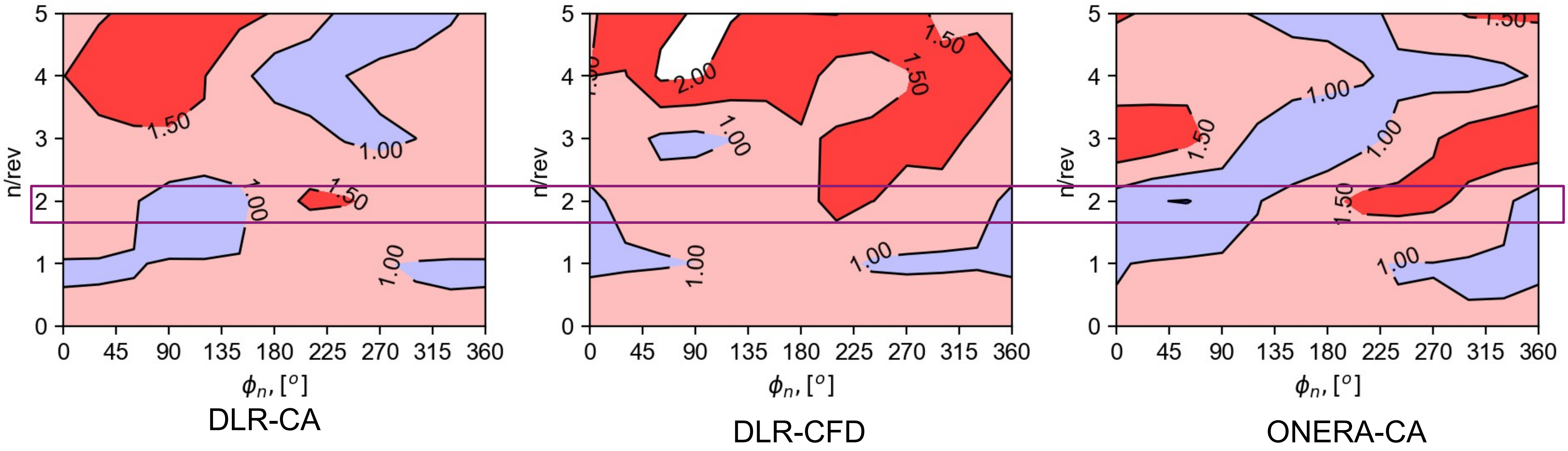
Actuation Sweeps – Full Sweep on Required Power



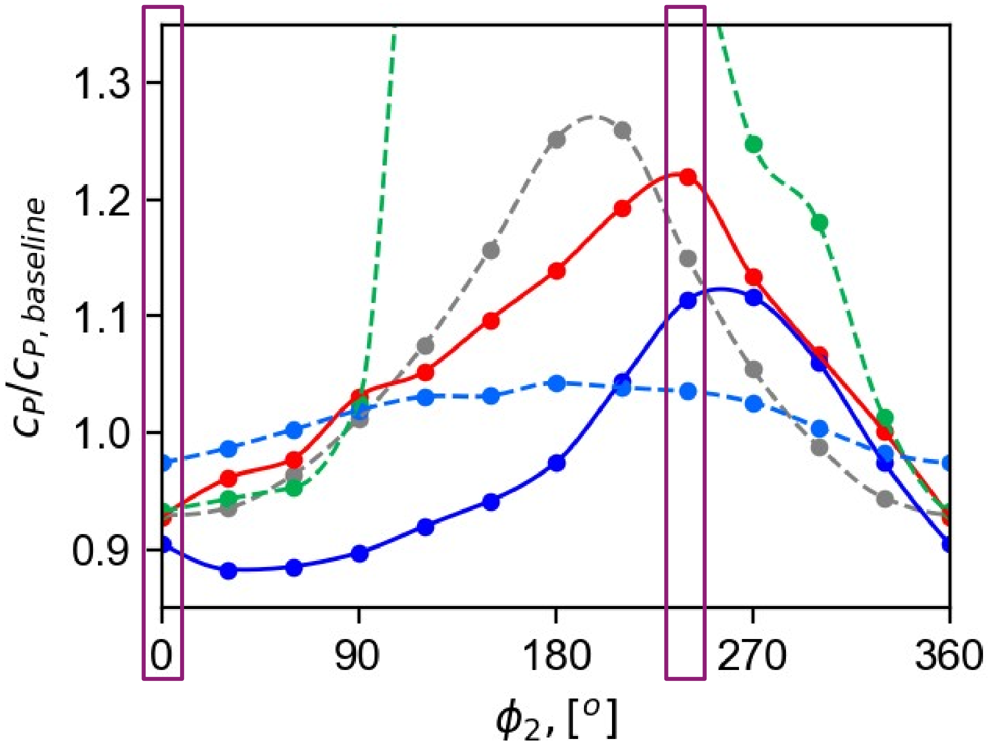
- Not all partners could compute the trend with all actuation results – results are relative to baseline at $c_T/\sigma = 0.13$
- 0/rev is only static offset, 1-5/rev computed in phase steps of 30°
- Most consistent and pronounced results found for 2/rev actuation – also greatest power reduction predicted by all partners

Actuation Sweeps – Full Sweep on Vibration Intrusion Index

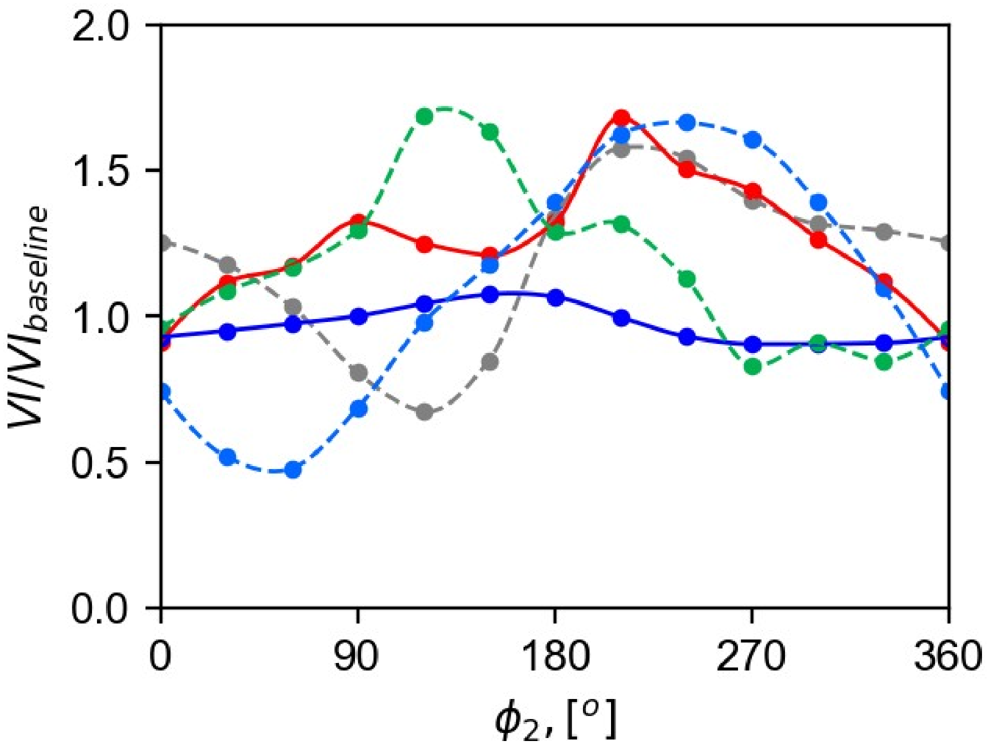


- Vibration Intrusion Index less consistent than required power
- This trend has already been observed for the thrust sweep
- However, the 2/rev actuation seems to be the common denominator for vibration reduction

Actuation Sweep @ 2/rev & c_T/σ = 0.13 – Integral Values



Required power (KU-CA cropped)



Vibration intrusion index

- Greatest benefit observed for required power for a phase around 330-60° for all partners
- A more diverse picture for VI, but likely reduced for a phase around 0° as well

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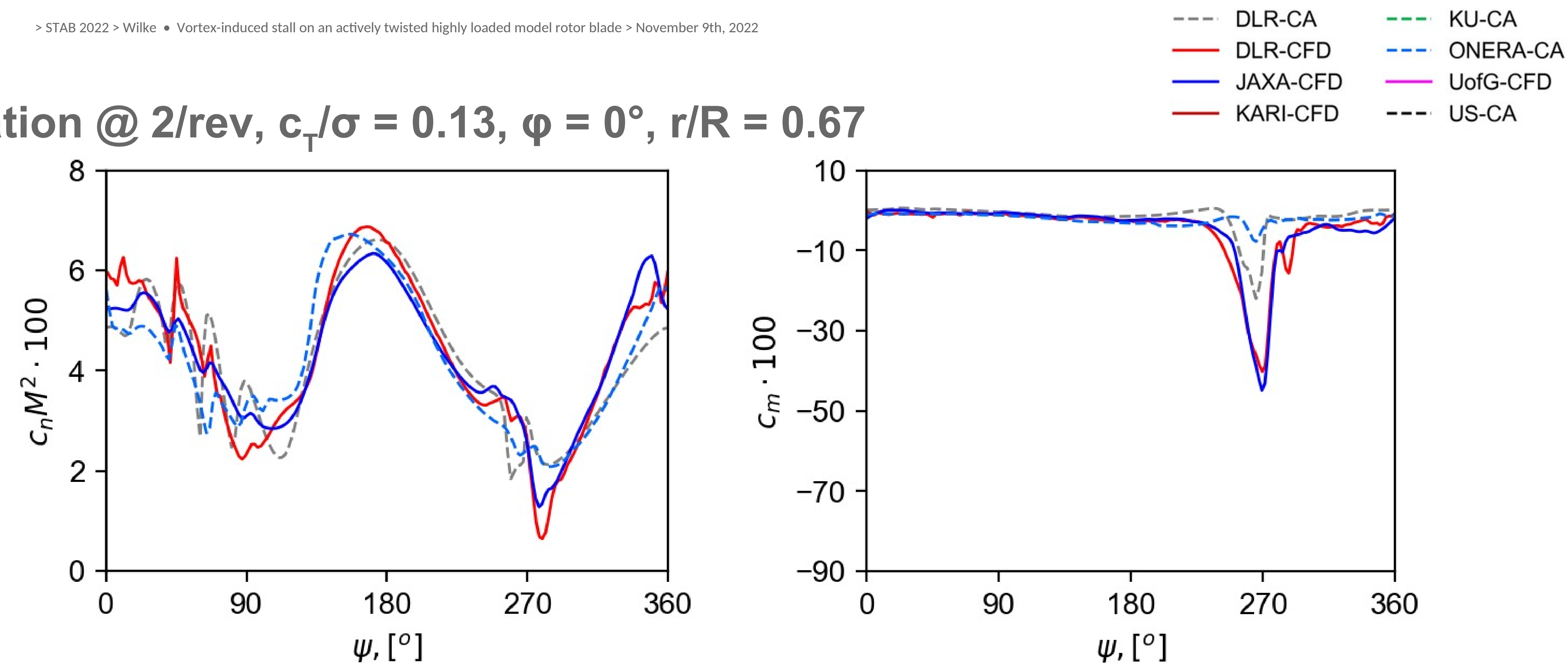
Actuation @ 2/rev, $c_T/\sigma = 0.13$, $\varphi = 0°$, r/R = 0.67

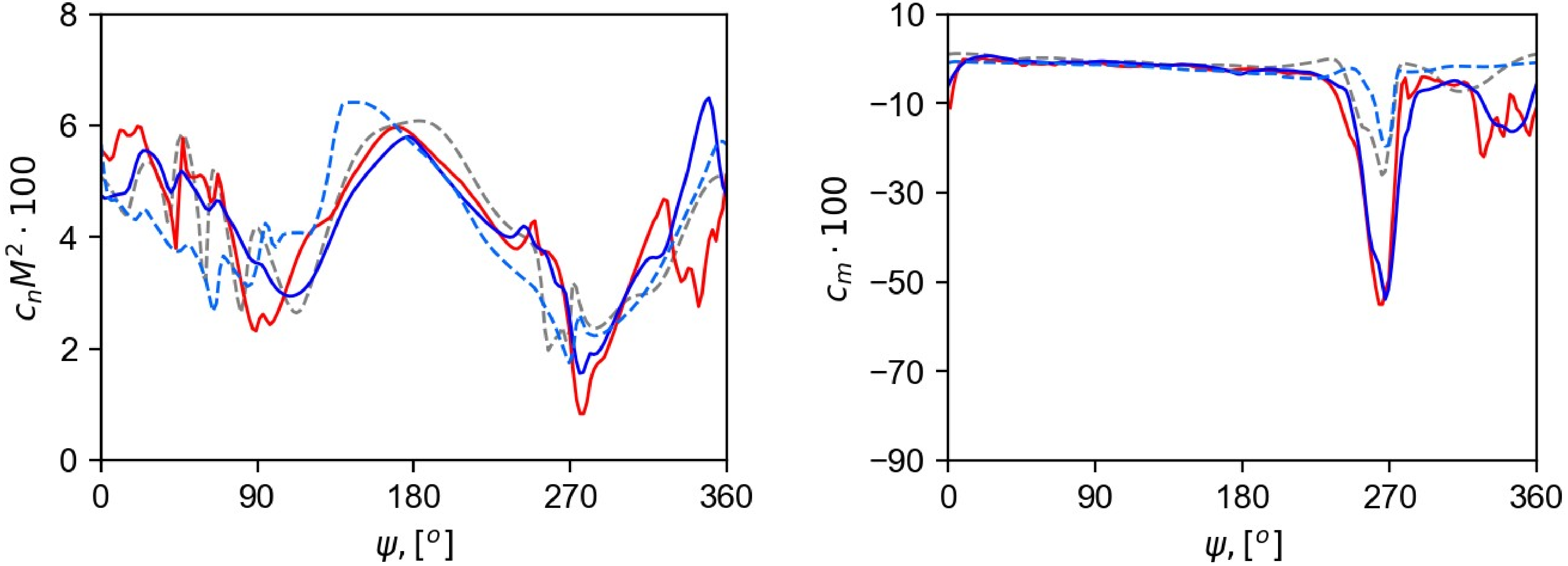


Normal load

Pitching moment

- Reduction of pitching moment stall for all partners
- DLR-CFD and JAXA-CFD in good agreement, DLR-CA in between ONERA-CA and CFD

Actuation @ 2/rev, c_T/σ = 0.13, φ = 240°, r/R = 0.67



Normal load

Pitching moment

- Increasing of pitching moment stall over baseline case
- Again, good agreement of DLR-CFD and JAXA-CFD with DLR-CA better on the normal loads, but similar to ONERA-CA on the pitching moment

Summary

- Investigated vortex induced stall test case at reduced RPM - “blind tested” prior of the wind tunnel test

- Thrust sweep
  - At the lower thrust regions, where no or little stall occurs, results are well aligned among the partners
  - Curves show a kink at the onset of stall
  - Post stall behavior often similar, but at different thrusts

- Actuation sweeps
  - Some agreement found, 2/rev actuation most promising as it is the common denominator
  - Required power and vibrations may be reduced at a phase of $\varphi \approx 0°$

- Generally, the overall trends where captured by most partners, but questions remain, which may only be answered by the wind tunnel experiment

- CA results deliver good trends in minutes to hours, whereas CFD results are produced in the order of days to weeks