

High Load Investigations of The Smart Twisting Active Rotor (STAR) - Comparison of Pre-test Simulations with Wind Tunnel Results

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ABSTRACT

The Smart Twisting Active Rotor (STAR) wind tunnel campaign has recently been completed. From the extensive test matrix, this paper focuses on the high-load operating condition, in which the rotor was investigated in both actuated and unactuated configurations under dynamic stall conditions. The experimental results are compared with numerical predictions generated both before and after the wind tunnel campaign. In addition to identifying beneficial active-twist settings for reducing rotor power consumption and vibration levels, the study assesses the predictive capabilities of the employed simulation methods, ranging from comprehensive rotorcraft analyses to coupled CFD/CSD simulations. For the unactuated rotor, reasonable agreement with the measured power consumption is achieved, whereas for the actuated rotor only some of the observed trends are captured. Accurate prediction of vibratory loads remains challenging. Nevertheless, the experiments demonstrate that active twist can reduce rotor vibrations by up to 42% compared with the unactuated baseline configuration.

INTRODUCTION

This paper presents the experimental and numerical results of the STAR wind tunnel campaign. STAR is the acronym for Smart Active Twisting Rotor. As helicopter rotors operate in a diverse range of flight conditions, the requirements for rotor blades are similarly diverse. In forward flight, a helicopter encounters shock waves on

the advancing side with (dynamic) stall on the retreating side all coupled with a soft and slender blade design. In contrast, fixed-wing aircraft mostly tackle the problem of varying speed requirements throughout their flight envelope through the application of flaps and slats. However, even such an adjustment might be insufficient for rotor blades due to their inherently unsteady nature, requiring a different blade on the advancing side than on the retreating side.

Thus, many active rotor blade controls have been proposed in the past. Chopra (Ref. 1) and Friedmann (Ref. 2) wrote excellent survey papers on this topic which the avid reader is referred to. Only a brief categorization is done here. Besides the conventional swashplate used for primary flight control, a higher harmonic controlled swashplate (Ref. 3) or a multi-swashplate control (Ref. 4) enables blade pitch actuating at higher frequencies than the 1/rev by the pilot. Depending on the selected control strategy, reductions in power, noise, or

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vibration, and to a certain extent a blend of these, may be achieved with respect to the non-actuated blade. Opposing the application of advanced swashplate approaches, other means of actuation exist. For example, pitch link actuation (Ref. 5) or flaps (Ref. 6) are means of active control devices for helicopter rotors. Another option is the application of actively twisting the blades. In the NASA/Army/MIT Active Twist Rotor (ATR) project (Ref. 7), piezo-electric elements actively twisted the rotor blades during their operation. DLR initiated the Smart Twisting Active Rotor (STAR) project in 2007 (Ref. 8). Partners from all over the world participate in the STAR project, namely: DLR, JAXA, ONERA, KARI, Konkuk University, NASA, and U.S. Army. The wind tunnel test was carried out in October, 2025 in the DNW-LLF wind tunnel with DNW contributing with additional wind tunnel days.

The present paper focuses on the high load cases of the STAR project. The cases investigate the dynamic stall phenomenon under high load in forward flight. Dynamic stall has also been subject of extensive research. A good overview is provided by Smith et al. (Ref. 9) explaining the current status on both measurement and simulation of the phenomenon. In the here presented case, the stall on the retreating side of the blade is triggered by and incoming vortex at around $r/R \approx 0.5..0.7$. In combination with a rapid pitch up motion of the blade, the maximum angle of attack of the respective blade sections are exceeded and the blade sections stall. However, for dynamic stalls, it is characteristic that a) the maximum lift coefficient is greater than the steady stall scenario, b) the negative pitching moment is strongly amplified as the stall vortex rolls over the blade. From an operational perspective this is a very undesired condition. The loss of lift is undesirable, but the occurring vibrations and dynamic loads on the control system are more critical. Thus, reducing this effect is very desirable.

The first accessible data from the wind tunnel results is compared against data predicted prior to the test, but also newly generated data. In 2022/2023 data has been produced based on initial predictions of the structural model and without the existence of wind tunnel data. Some of these results have already been disseminated previously as an overview (Ref. 10) or dedicated paper for the high load condition (Ref. 11). The current work also includes simulation results produced with the updated structural model, where the built blades have been analyzed by Chang et al. (Ref. 12). Consequently, this paper provides an assessment of the predictive capabilities of the different state-of-the-art simulation tools employed for the high load cases featuring dynamic stall while identifying areas where further methodological improvements are required.



Figure 1: General legend of the paper

METHODOLOGY

The simulations results are categorized into three groups: the experimental results (EXP), comprehensive analysis (CA) results, or CFD/CSD based (CFD) results. Since nine groups including the DNW have contributed data, a common legend is established for the paper, as shown in Fig. 1. The color, line-style and marker conventions are maintained consistently throughout the paper with the exception of the grid sensitivity study. Comprehensive analysis results (CA) are represented with dash lines with 'x' symbols for marking the computed data points, CFD results are shown as solid lines with triangles, and experimental data are represented by black dots. Rather than describing each simulation software individually, the most relevant modeling parameters are summarized in Table 1 for the CA only methods and in Table 2 for the CFD coupled results. A more in-depth explanation is found in the 2022 overview paper by van der Wall et al. (Ref. 13). Specific changes with respect to the 2022 publication in spatial or temporal resolution are reflected in Table 1 and Table 2.

It is worth highlighting that the variation of spatial and temporal resolution is high among the CA codes, as well as their assumed initial core radius and whether or not a fuselage or terminal box is included. Conversely, most partners doing CFD are able to include the terminal box at the blade root being a blunt body housing the wiring of the actuators. All CFD partners also included the fuselage. The variation of background grid resolution is not as large, but the temporal resolution is varying similarly, yet an order of magnitude lower than the CA simulations. The application of laminar-turbulent transition modeling is also different among the partners.

From this preliminary discussion, different results are expected as the best practices are tuned for the capabilities of the individual simulation packages applied.

RESULTS ORGANIZATION

The characteristic data of the rotor along the utilized operating conditions are listed in Table 3. Here, it is distinguished between pre- and post-test conditions. While prior to the test, ISA sea level conditions were assumed, the actual operating conditions in the wind tunnel were minorly different. The shown values represent the average over all the data points recorded for the high load

Table 1: Summary of comprehensive code setups. box - modeling of the terminal box at the blade root, init. tip core - initial core radius of the rolled-up tip vortex model in $r_{c,0}/c$

	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
aero elements	20	16	30	28
$\Delta\psi[^\circ]$	2°	15°	5°	15°

Table 2: Summary of CFD setups. order - theoretical inviscid flux scheme order, transition - how laminar-turbulent transition is included, blade - resolution of the blade mesh in chordwise x normal x spanwise direction, background - spacing of the Cartesian grid area relative to the chord length

	DLR-CFD	JAXA-CFD	KARI-CFD	ONERA-CFD
box	yes	yes	yes	no
fuselage	yes	yes	yes	yes
order	4	4	2	2
turbulence	SA-DDES-R	Menter SST	SA	Menter SST
transition	empirical	γRe_θ	no	no
blade resolution	128x64x128	141x81x157	-	161x81x161
background $\Delta x/c$	14%	10%	15%	11%
total # grid pts	15 M	88 M	29 M	40 M
$\Delta\psi[^\circ]$	0.33°	0.1°	1.0°	0.25°

Table 3: Key rotor metrics and reference values

variable	pre-test	post-test
Radius [m]	2	
chord [m]	0.121	
RPM	521	520
advance ratio	0.3	
shaft angle α_q	0°	
density of air [kg/m^3]	1.226	1.190
temperature [K]	288.15	290.6
Step 1 c_T/σ	0.0639 ... 0.17	0.0639 ... 0.125
Step 2 c_T/σ	0.13	0.12
Step 2 frequencies	2,3,4/rev	
Step 2 phases	0 ... 330° in steps of 30°	
Step 1 & 2 trim	zero hub moments	

Table 4: Grid cells of grid density study.

	coarse	intermediate	fine
	blade		
chordwise	128	160	256
normal	64	80	128
radial	128	160	256
blade total	1e6	2e6	8.4e6
	fuselage		
fuselage total	1.1e6	1.9e6	8.4e6
	background grid		
$\Delta x/c$	14%	10%	7%
background total	11e6	23e6	78e6
setup total	14e6	33e6	119e6
$\Delta \psi [^\circ]$	0.25	0.25	0.125

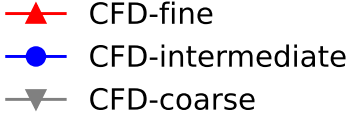


Figure 2: Specific legend for the grid sensitivity study

cases. For the wind tunnel test and the simulations, a three-component trim is sought: The thrust force coinciding with the lift force due zero effective shaft angle and zero roll- and pitching moments. Prior to the test, a few partners were able to run thrust polars up to a $c_T/\sigma = 0.17$. In the wind tunnel, only $c_T/\sigma = 0.125$ could be achieved. The maximum collective and cyclic pitch control angles are limited by the servo/swashplate system of the model, and in these cases, the cyclic pitch control limit has been reached during the wind tunnel test, thus the interesting question on where maximum thrust would be located for this rotor in this condition cannot not be answered. It is additionally highlighted that this test case is set to run at 50% of the nominal RPM as very initial simulations indicated that the measurements limits of the scale will likely be exceeded, but also the available power would be insufficient to operate at $c_T/\sigma > 0.11$. In combination with very strong torsional deformation of more than 10° that has been predicted, this test case was deliberated altered to safely drive the rotor into dynamic stall with moderate deformations and high-power requirements.

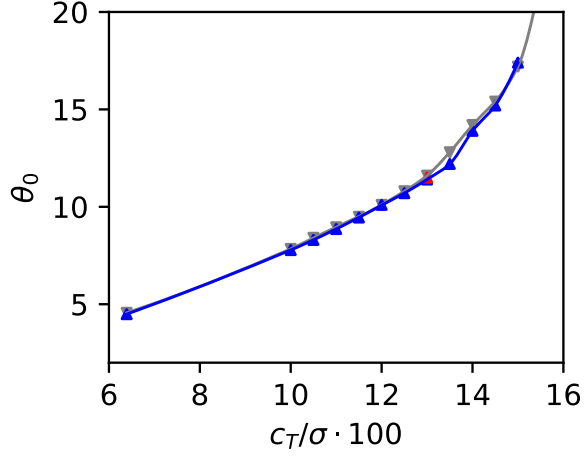
PRELIMINARY GRID STUDY

In the previous publication on the high load case (Ref. 11) prior to the wind tunnel test, fair discrepancies between partners have been observed. In effort to identify the sensitivities of the results with respect to simulations settings, DLR looked into the impact of CFD grid resolution. This would also serve as a guideline for further studies, in particular when it comes to running the nu-

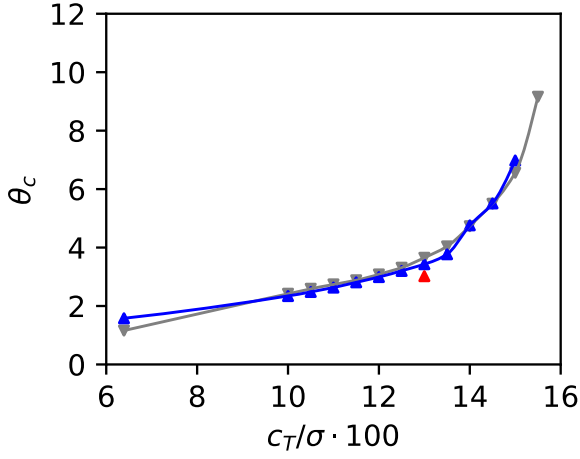
merous data points for the actuation studies (36). The methodology for DLR-CFD is the same as stated previously with the exception that the grids are separated into coarse, medium and fine grids. The characteristics of these grids are listed in Table 4 and the according legend for this study in Fig. 2. For the coarse and intermediate grids, all data points are run, whereas due to the significant cost increase on the finest grid only a single point has been computed. It took roughly 9 months to perform this simulation due to slow flow solver convergences issues, insufficient parallelization and slow trim convergence requiring 10 coupling steps to consider this case converged. In contrast, the intermediate grid required roughly 4 weeks for the same data point and the coarse grid 2 weeks. These numbers also include queuing times. Both coarse grids showed a better trim convergence within 4 coupling steps each. The predicted structural model prior to the blade measurements has been used for these cases as the measurements have simply not been available at that time.

$$VI_4 = \sqrt{(0.5F_{x,4})^2 + (0.67F_{y,4})^2 + (1.0F_{z,4})^2} / W_0 + \sqrt{(M_{x,4})^2 + (M_{y,4})^2} / (W_0 R) \quad (1)$$

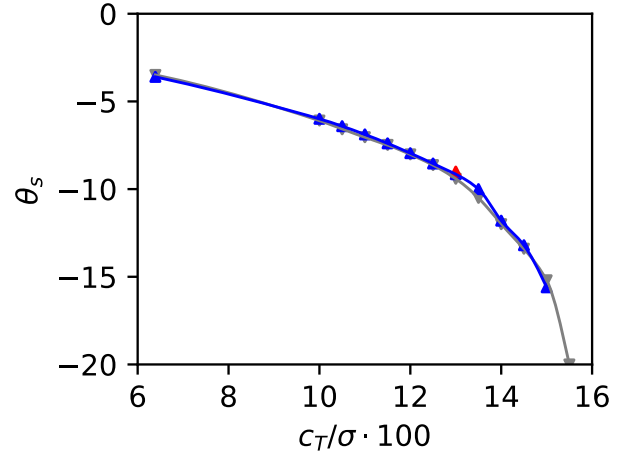
The trim control angles $\theta_0, \theta_c, \theta_s$, required power c_p/σ and the Vibration Index for 4/rev VI_4 are plotted in Fig. 4. At a first glance, the correlation of the trim control angles is close to each other indicating that the flight mechanical result, the obtained thrust, roll and pitching moments are of little dependence with respect to the grid. The fine grid shows a mild deviation with respect to θ_c . Around $c_T/\sigma \approx 0.13$, a bit of a waviness is observed, which is also found in the trim convergence. Looking at the required power c_p/σ , a general good agreement is found. The finer grids yield less required power which is correlated with the effective reduction of numerical viscosity on the finer grids. The difference between the fine and intermediate grid are smaller than the intermediate to the coarse grid being consistent with the general expectation in CFD that the error decreases towards finer grids. The Vibration Index VI_4 has the largest deviation among the metrics across the different grid sizes with the largest gap between the coarse and intermediate grid for the lowest thrust $c_T/\sigma = 0.0639$. The Vibration Index is defined as a weighted sum of squared hub forces and moments normed by a reference weight and the rotor radius and with the underscore 4 relating to the fact that 4/rev amplitudes of these forces and moments are considered, see Eq. (1). The reference weight is 900N as the rotor is operated at half RPM. The delayed increase of the VI_4 for the intermediate grid with respect to the coarse grid is associated with the delay stall onset correlating with the required power. Since there is only one datapoint for the finest grid, no deduction on the overall behavior can be made. It is assumed that the increase of VI_4 comes from improved resolution and the significantly



(a) Collective pitch angle

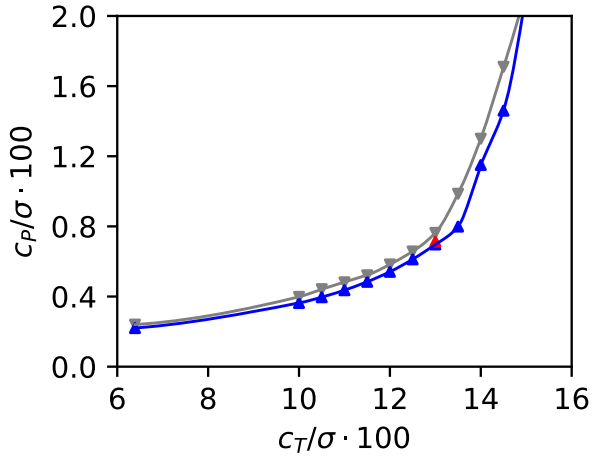


(b) Lateral cyclic pitch angle

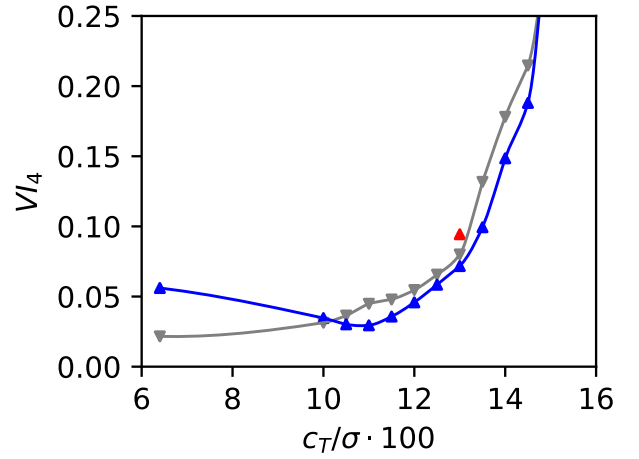


(c) Longitudinal cyclic pitch angle

Figure 3: Pitch angles over thrust variation



(a) Power coefficient



(b) 4/rev Vibration Index VI_4

Figure 4: Integral metrics over thrust variation for different grids

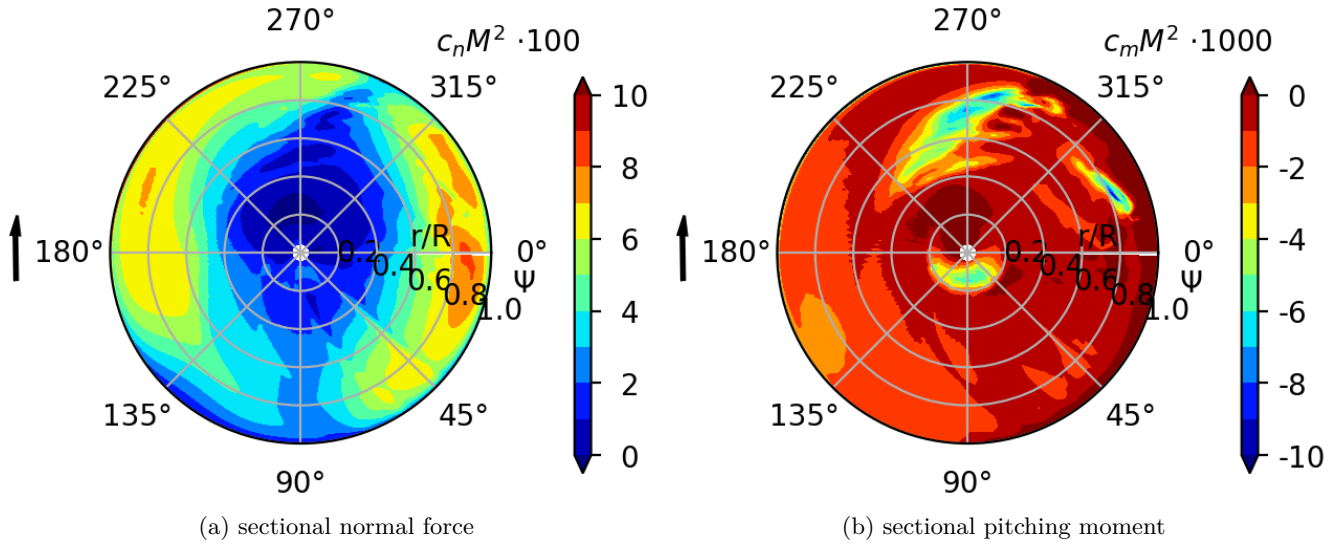


Figure 5: Loads $c_T/\sigma = 0.13$ for coarse grid

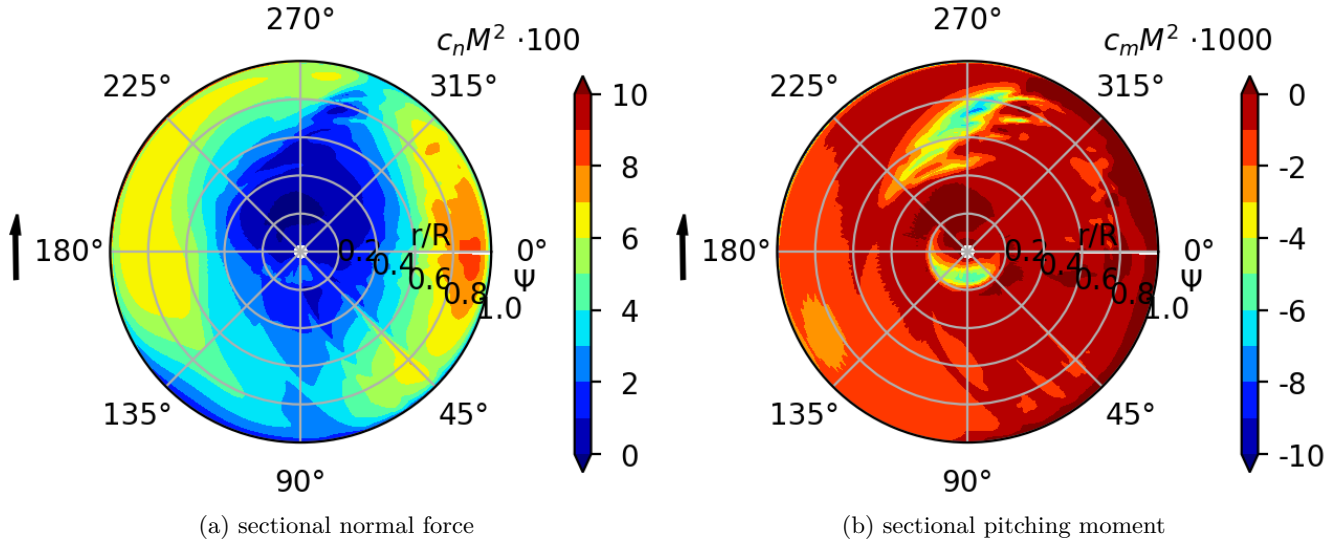


Figure 6: Loads $c_T/\sigma = 0.13$ for intermediate grid

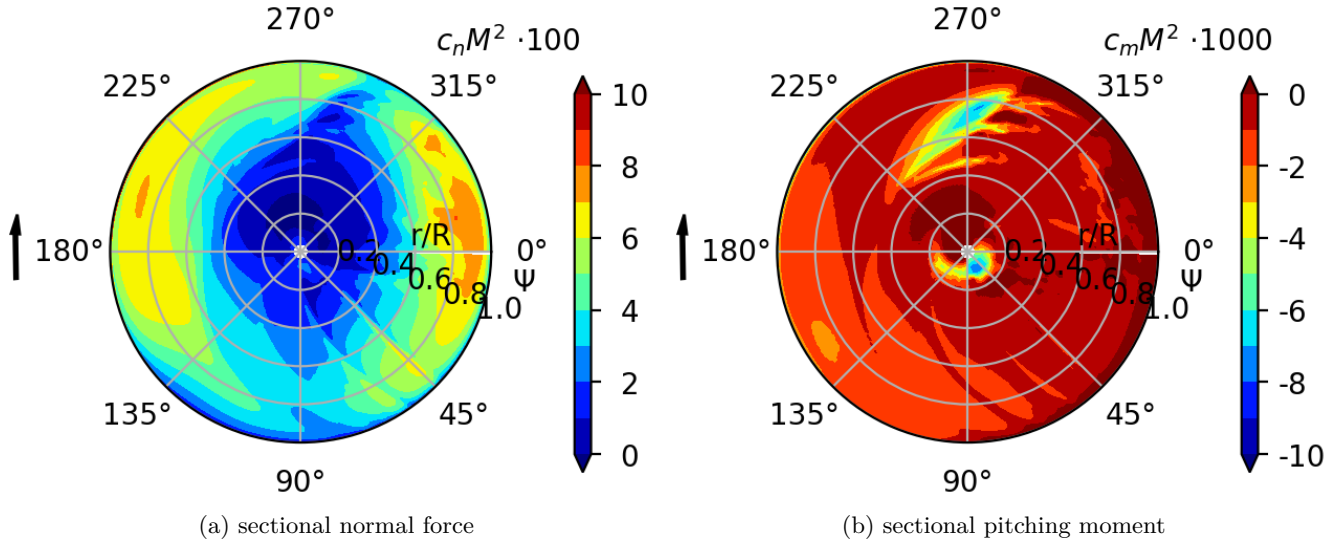
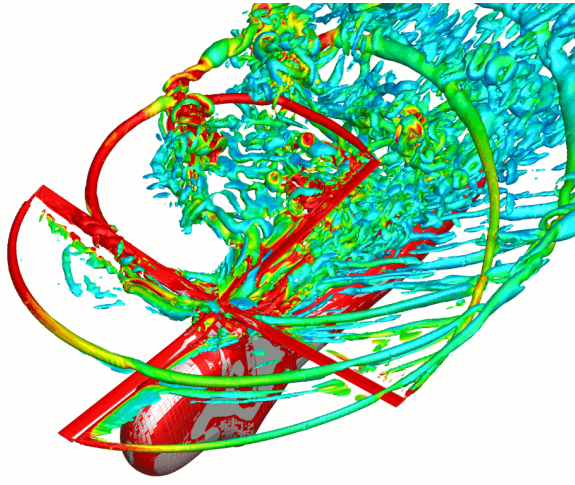
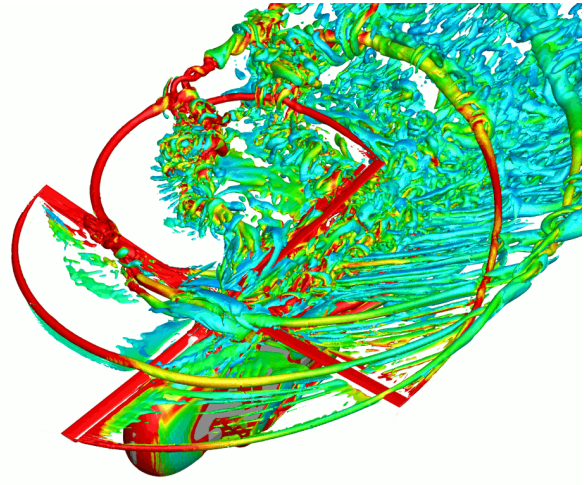


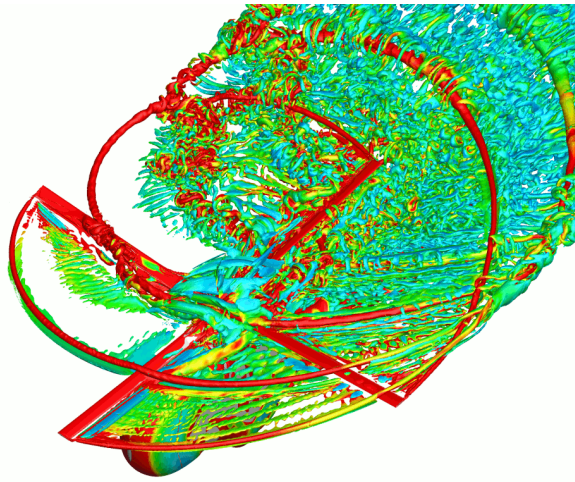
Figure 7: Loads $c_T/\sigma = 0.13$ for fine grid



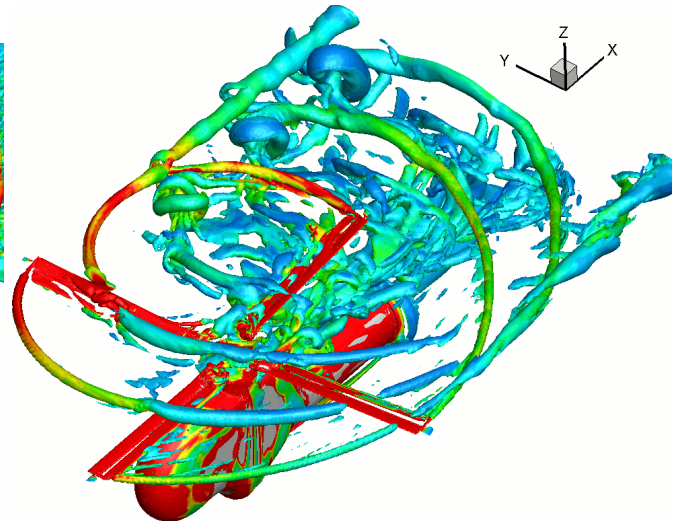
(a) DLR-CFD coarse grid



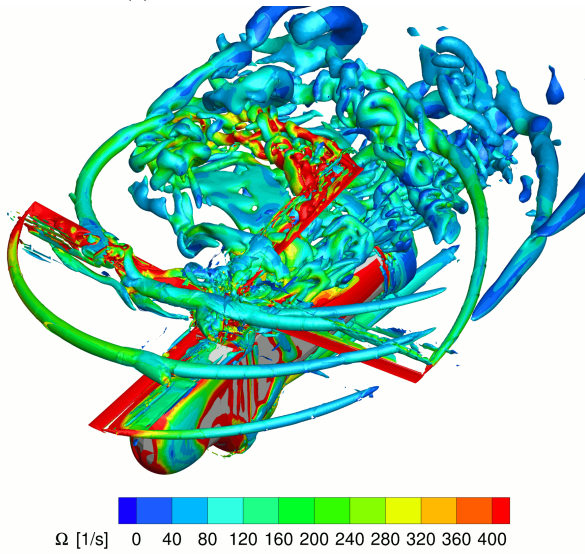
(b) DLR-CFD intermediate grid



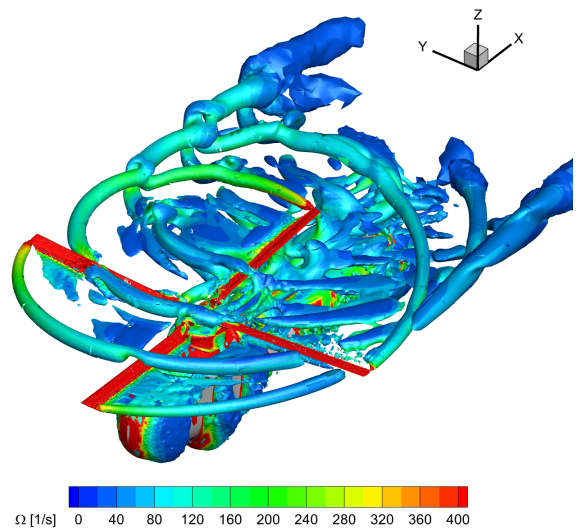
(c) DLR-CFD fine grid



(d) JAXA-CFD



(e) ONERA-CFD



(f) KARI-CFD

Figure 8: Vorticity plots at $c_T/\sigma = 0.13$

stronger secondary vortex presence found, thus, leading to more vibrations.

In order to better comprehend the physics, the sectional normal force and the pitching moment are plotted for $c_T/\sigma = 0.13$. For a qualitative assessment of the flow physics, Fig. 8 visualizes the results for the DLR setups and readily includes the visualizations of the other partners to be discussed at a later stage. The load plots reveal that at this operational condition, a moderate dynamic stall occurs. It begins at $\psi \approx 225^\circ$ and $r/R \approx 0.5$ and diagonally spans to about $\psi \approx 290^\circ$ and $r/R \approx 0.9$. This is best visible by the drop in pitching moment in this area, and to a lesser extent by the loss of normal force ($\sim$ lift), which onsets later than the pitching moment. Correlating this observation with the flow visualizations in Fig. 8, where the retreating side blade is at $\psi = 270^\circ$, the separation is clearly triggered by the preceding tip vortex and merges with the stall vortex of the respective blade sections. This phenomenon is present for all simulations and more distinctively seen on the fine grids. The presence of the secondary vortices increases with grid resolution. It is concluded from the load plots, that the secondary vortices have a secondary impact on the loads and result in higher frequent content of the loads. This is visible in the not shown line plots for these cases here and will be discussed in the next section. For the grid density study, the economical choice for further studies lies on the coarse and intermediate grids. The slight increase in accuracy on the finest grid does not justify its use for a broader parametric study due to its significant cost increase. It is noted that on the coarsest grid, a second stall phenomenon is found for $\psi \approx 330^\circ$ and $r/R \approx 0.8$. While the severity of this onset is reduced for the better resolved simulations, it is accepted to use the coarse setup for the next studies.

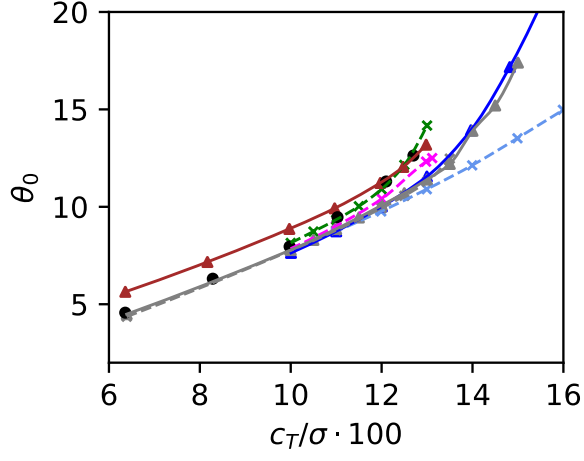
RESULTS USING PREDICTED STRUCTURAL PROPERTIES

This section presents the results obtained during the earlier stages of the STAR project and have been generated in 2022/2023. They have been published in van der Wall et al. (Ref. 10) and Wilke et al. (Ref. 11). Thus, these results are considered true blind tests or pre-dictions, as the blade structural properties have not yet been determined by Chang et al. (Ref. 12). The reason why they are repeated here is to assess the predictive capabilities of current state-of-art tools prior to a wind tunnel test.

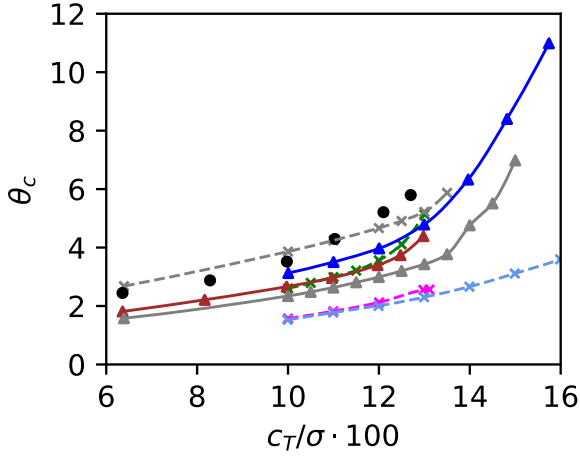
The presentation style is similar to the previous section with the pitch control angles, required power and vibration plotted in Fig. 10. The simulation results correlate well among the partners for lower range of thrust up to about $c_T/\sigma \approx 0.13$ were depending on the simulated onset of stall, the partners start at lower or higher thrust to shift from a linear collective thrust behavior to a quadratic behavior. The offset of the simulations with respect to the experiment is little for the lower

thrusts. The simulations deviate more for higher values past $c_T/\sigma \approx 0.13$. Here, KARI-CA is closest to the experiment, while ONERA-CA deviates the most. The DLR-CA, DLR-CFD, and JAXA-CFD results are close to each other, whereas the other CA results have a larger spread. KARI-CFD agrees well for the higher thrusts, yet predicts the largest collective pitch angle among all partners at the lower thrust. The lateral cyclic pitch angle θ_c has a similar trend of a linear range up to a certain point before moving quadratically as the collective pitch angle θ_0 . The spread among lateral cyclic pitch angle θ_c is generally larger among the partners and also relative to the experiment than it has been for collective pitch angle θ_0 . Here, DLR-CA gets closest to the experiment followed by JAXA-CFD. KARI-CFD and DLR-CFD underpredict the lateral cyclic pitch angle while having similar trends. ONERA-CA and US-CA are equally far away from the experiment. The longitudinal cyclic pitch has a reduced linear range and shows the curved behavior already at a $c_T/\sigma \approx 0.1$. The simulations mostly align well with the experiment up to this point, afterwards the onset of the curve is correlated with the stall onset. The US-CA results are closest to the experiment when ignoring the final data point and KARI-CFD being second closest followed by KU-CA. DLR-CA, DLR-CFD, JAXA-CFD and KARI-CFD simulations align similarly well as they have for the collective pitch θ_0 but have a larger offset to the experiment. The ONERA-CA results have again the largest offset. The shape of the required power curve is very similar to the collective pitch angle θ_0 albeit with a larger spread among the computational methods. For the lower thrust, DLR-CA and DLR-CFD align well with the experiment, with KARI-CA being closest to the experiment for the full thrust range. US-CA captures the power rise past the stall point slightly better than DLR-CA and ONERA-CA. DLR-CFD and JAXA-CFD agree well with each other. They predict the least required power among the partners, whereas KARI-CFD predicts the highest required power among all partners throughout the curve, but match the last experimental data point best. Moving over to the Vibration Index computed with the 4/rev hub loads VI_4 , the results are very mixed. JAXA-CFD results are closest to the experiment, with CA results having mostly odd trends with the exception of KU-CA. KARI-CFD has a late onset of this metric with respect to rotor thrust and DLR-CFD is even further delayed.

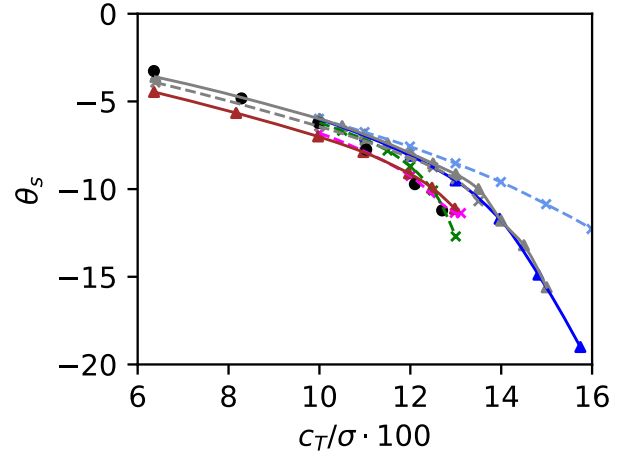
The airloads are plotted for the thrust of $c_T/\sigma = 0.1, 0.13, 0.15$ in Fig. 11, Fig. 12, and Fig. 13 respectively. Without the prior knowledge of the experiment, the reference thrust was set at $c_T/\sigma = 0.13$. While the reference thrust was then changed during the wind tunnel test where the maximum attainable thrust was $c_T/\sigma = 0.125$, this section remains with $c_T/\sigma = 0.13$ as this was the agreed upon reference thrust prior to the experiment. The sectional loads are extracted at $r/R = 0.67$ corresponding to a location that has been equipped with pres-



(a) Collective pitch angle

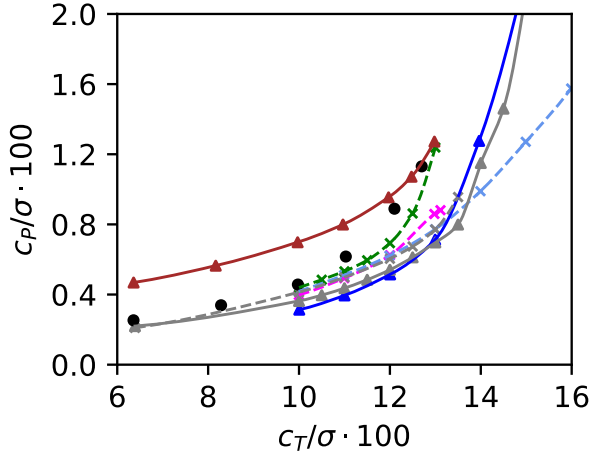


(b) Lateral cyclic pitch angle

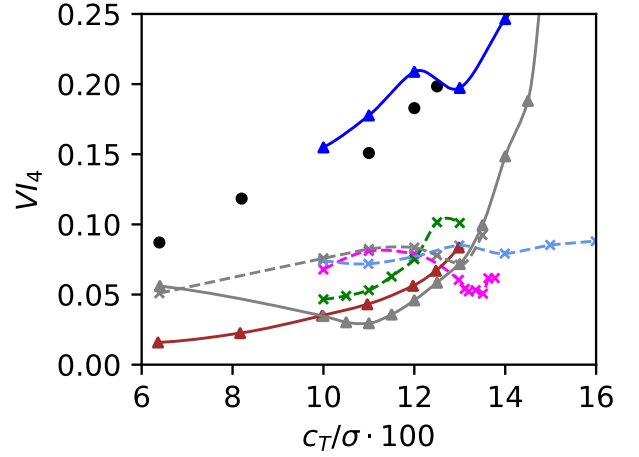


(c) Longitudinal cyclic pitch angle

Figure 9: Pitch angles over thrust variation

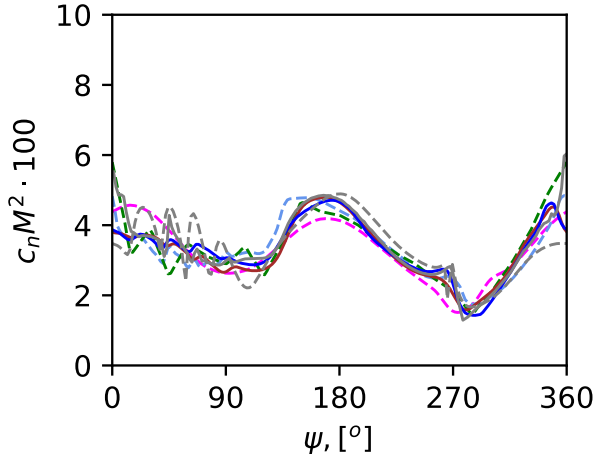


(a) Power coefficient

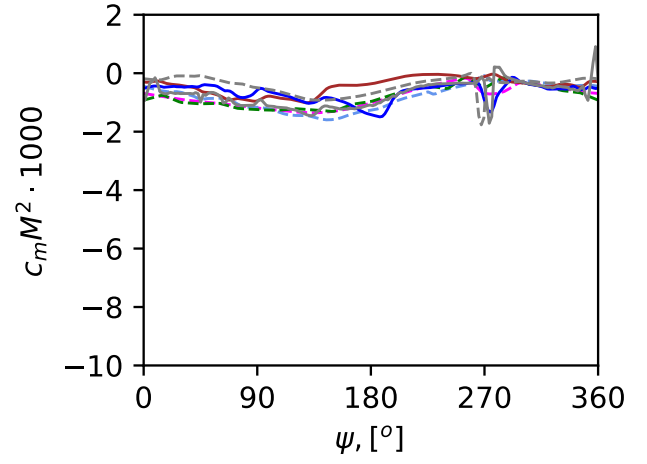


(b) 4/rev Vibration Index VI_4

Figure 10: Integral metrics over thrust variation with predicted structural data

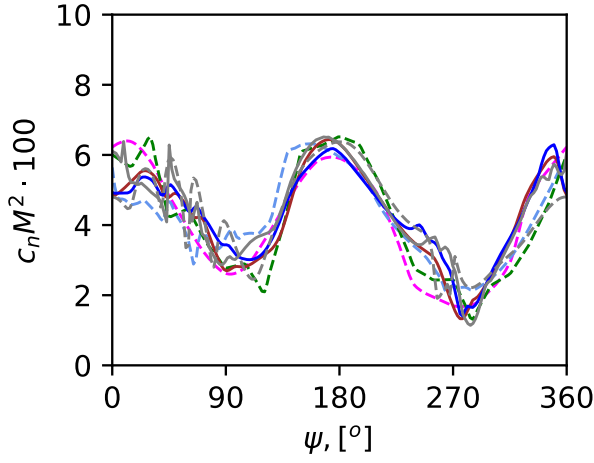


(a) $c_n M^2$

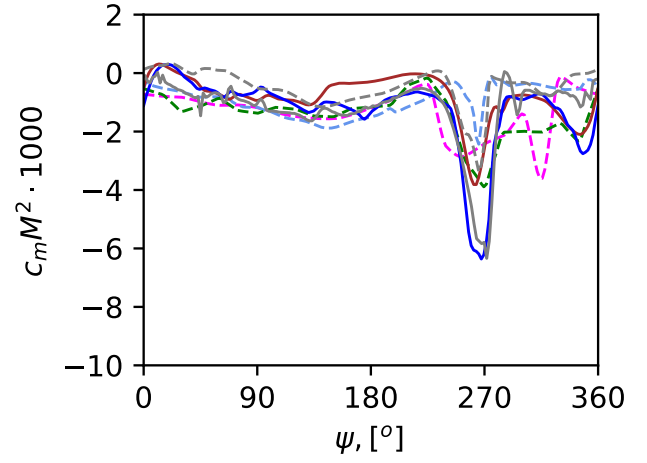


(b) $c_m M^2$

Figure 11: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.10$ with predicted structural data

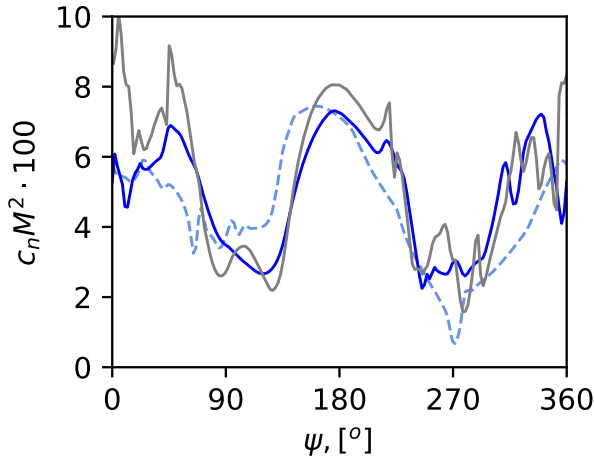


(a) $c_n M^2$

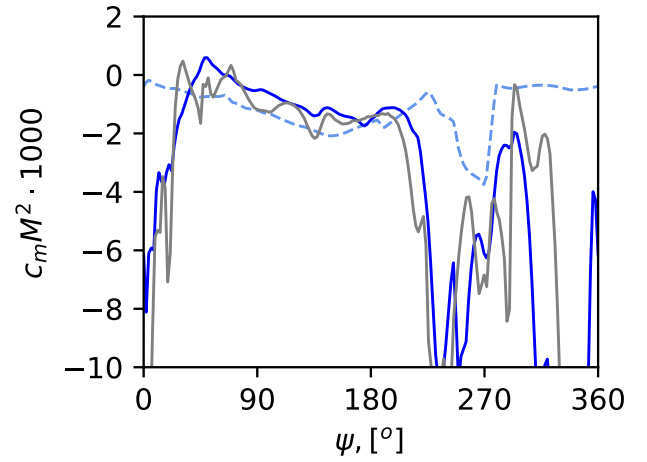


(b) $c_m M^2$

Figure 12: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.13$ with predicted structural data



(a) $c_n M^2$



(b) $c_m M^2$ - deliberately cropped to keep the scale

Figure 13: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.15$ with predicted structural data

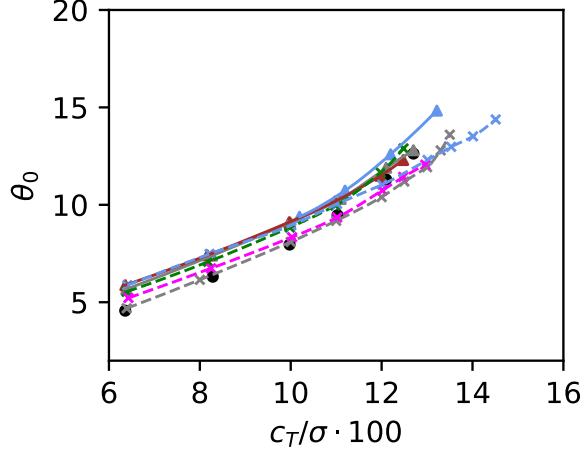
sure sensors during the wind tunnel test deemed closest to the occurring dynamic stall event. Unfortunately, the processing of this data has not been done at time of this writing. For the lower thrust condition ($c_T/\sigma = 0.1$), the normal force and the pitching moment behave relatively smooth at $\psi = 270^\circ$. The exception is DLR-CA which also resolves a strong BVI event on the aft/advancing side ($\psi \approx 0^\circ..90^\circ$), and to a weaker extent also found by DLR-CFD and JAXA-CFD. US-CA simulates the least severity of the stall phenomenon. The negative pitching moment peak at $\psi \approx 270^\circ$ indicating a moment stall is visible for DLR-CA, DLR-CFD and JAXA-CFD, with a KU-CA and US-CA hinting at it. KARI-CFD does not show signs of the pitching moment stall at the lower thrust. At the intermediate thrust ($c_T/\sigma = 0.13$), the phenomenon is greatly amplified especially for the pitching moment. In contrast to the even higher thrust ($c_T/\sigma = 0.15$), the stall event is still locally contained. All partners capture the negative pitching moment peak with DLR-CFD and JAXA-CFD resolving the strongest peak. At the higher thrust ($c_T/\sigma = 0.13$), the impact of the secondary vortex structures is well visible for the DLR-CFD result and to a lesser extent for the JAXA-CFD simulations and barely visible for the KARI-CFD simulations, see flow visualizations in Fig. 8. The major reason in the differences is explained with the class of the turbulence model DLR-CFD utilizes (D)DES while JAXA and KARI stayed with conventional URANS. The ONERA-CA results are moderate with respect to this and are more of a further amplification of the intermediate thrust results.

RESULTS WITH MEASURED STRUCTURAL PROPERTIES

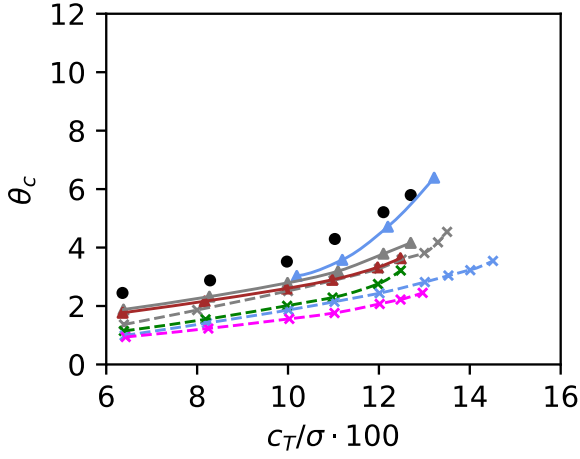
The trim controls, power and vibration for increasing thrust are presented in Fig. 14. In this section, this data has been compiled with the updated structural properties as determined by Chang et al. (Ref. 12). DLR-CA and ONERA-CFD results were submitted prior to the wind tunnel test, whereas the remaining parties carried out the simulations after the test. Thus, data was requested up to $c_T/\sigma = 0.125$ corresponding to the maximum thrust operated in the wind tunnel. The collective pitch angle θ_0 moved to higher values for the same thrust for the simulations with respect to the pre-test simulations. The spread between the partners is also reduced, but grows with thrust as previously obtained for the predicted structural properties. DLR-CA is in very good agreement for the lower thrusts up to $c_T/\sigma = 0.1$, whereas DLR-CFD and KARI-CFD match the experiment best at the highest thrust. The greatest discrepancy for the control angles is found for the lateral cyclic pitch angle θ_c , where ONERA-CFD has the best alignment for the higher thrusts and DLR-CFD and KARI-CFD for the lower thrusts. US-CA has the largest offset from the experiment. For the longitudinal cyclic pitch angle θ_s , the simulations all underpredict the value for thrusts lower than $c_T/\sigma = 0.11$ and

overpredict them slightly at higher thrusts with the exception of KU-CA. Here, ONERA-CA has the largest offset and ONERA-CFD the smallest. The required power trend is well matched by ONERA-CFD and KU-CA. DLR-CA, DLR-CFD, KU-CA, ONERA-CA, and US-CA matches well at lower thrust and have a delayed increase of the required power for higher thrusts with respect to the experiment. KARI-CFD generally overpredicts the required power similar to the prior simulation for the predicted structural properties. The large diversity of results for the VI_4 metric is still given as previously observed for the results generated with the predicted structural properties. The exception is ONERA-CFD being closest to the experiment, while the other partners generally underpredict this metric. The vibration metric of DLR-CA and US-CA drops off at the highest thrust after an increase at intermediate thrust contradicting the experimental trend, while DLR-CFD, KARI-CFD, KU-CA and to a lesser extent ONERA-CA replicate at least the increase of VI_4 with thrust.

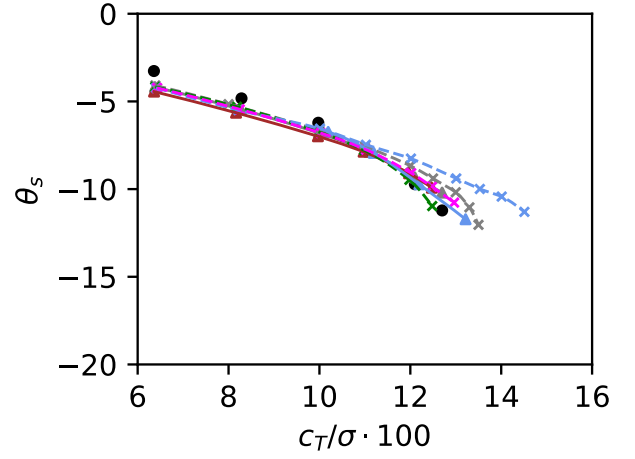
Due to the mostly poor correlation between the simulations and the experiment of the VI_4 metric, the hub force and moment components accumulating to this metric are plotted in Fig. 16. For the streamwise force component $F_{x,4}$, the partners generally underpredict the measured value. A kink is recorded in the experiment which is not replicated by any of the simulation results. The increase towards higher thrust is captured by all except for DLR-CA and ONERA-CA. For the lateral force component $F_{y,4}$, the correlation is improved with DLR-CFD being closest overall to the experiment and KARI-CFD following the trend closely. US-CA behaves oddly with strong increase of the metric and a stagnating metric over the remaining thrust regime. DLR-CA reduces this metric with higher thrust. DLR-CFD, ONERA-CA, ONERA-CFD, KARI-CFD and KU-CA capture the trend of an increase of the force amplitude similar to the experiment albeit at a lower level. The vertical component $F_{z,4}$ has a generally increasing trend. ONERA-CFD results are close to the experiment at higher thrust with a dip at $c_T/\sigma = 0.12$. DLR-CFD is close for the higher thrusts while their curve starts at a much lower values than the experiment. KARI-CFD has a similar trend with a lower values at higher thrusts. US-CA shows a drop-off after $c_T/\sigma = 0.12$. DLR-CA first increases and then drops off with a wiggle at the highest thrust not resembling the experimental data. KU-CA first reduces this metric with thrust and then increases towards the final thrust. Again, in general at a too low level with respect to the experiment. Investigating the moment components, they are also both underpredicted with the exception of ONERA-CFD capturing the increasing trend with the exception of the first data point for the roll moment. For the other codes, the predicted values are generally too small in contrast to the experiment with ONERA-CA being close for thrusts below $c_T/\sigma \leq 0.1$. Relating these findings with the VI_4 , one can assess that numerically the largest value



(a) Collective pitch angle

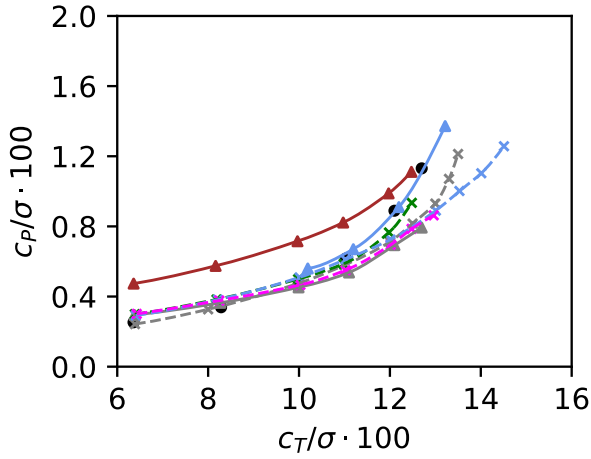


(b) Lateral cyclic pitch angle

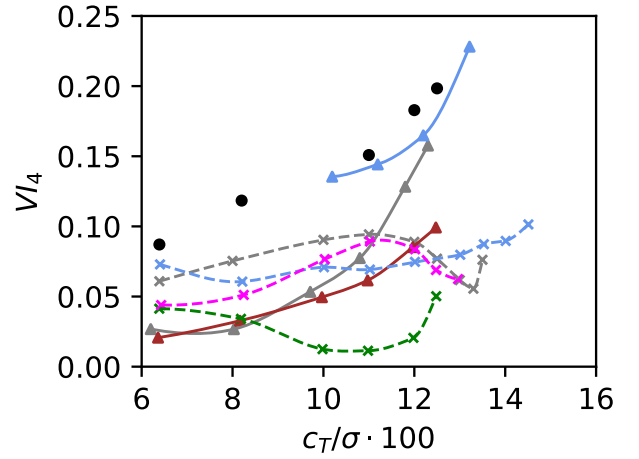


(c) Longitudinal cyclic pitch angle

Figure 14: Pitch angles over thrust variation

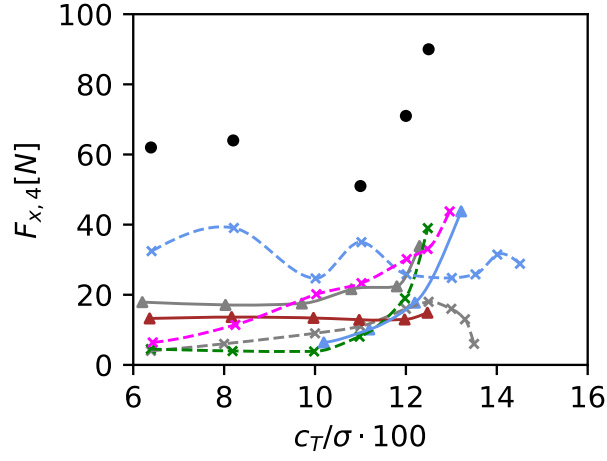


(a) Power coefficient

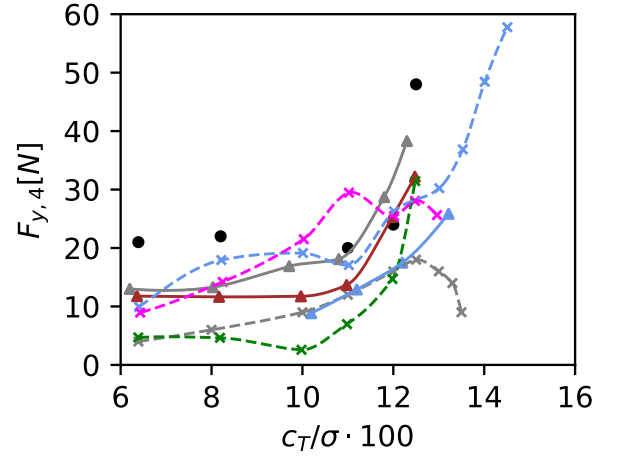


(b) 4/rev Vibration Index VI_4

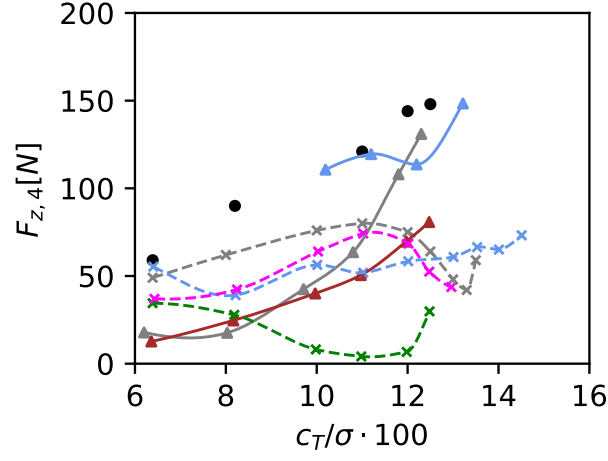
Figure 15: Integral metrics over thrust variation with the measured structural data by Chang et al. (Ref. 12)



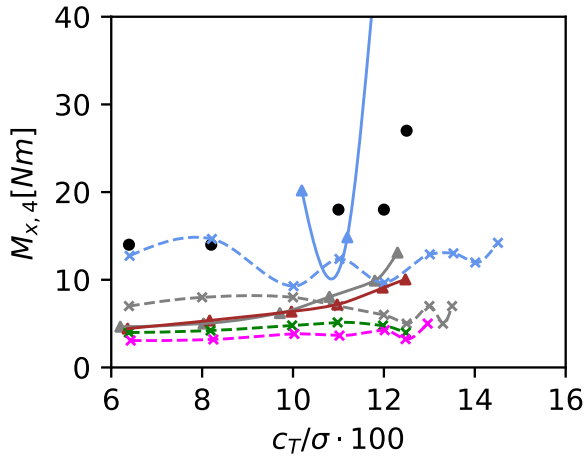
(a) Streamwise force component



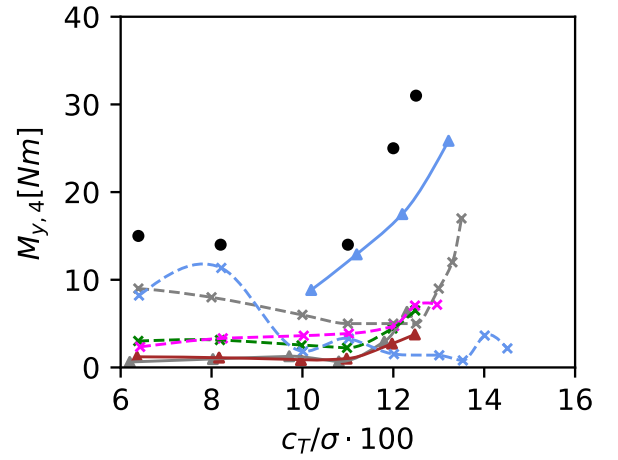
(b) Lateral force component



(c) Vertical force component

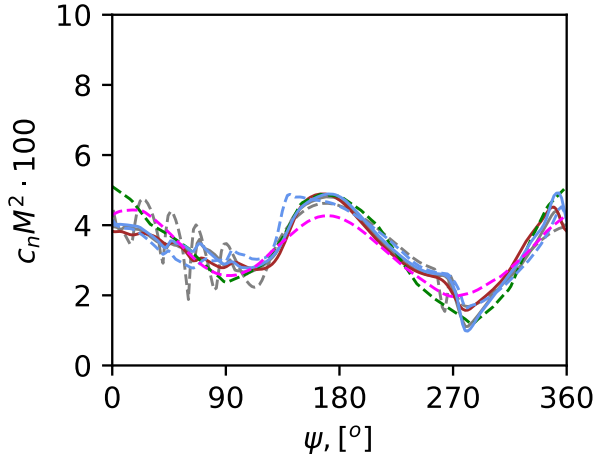


(d) Roll moment component

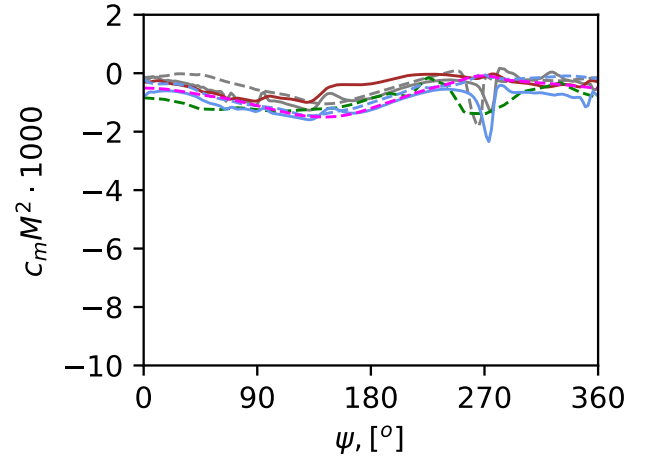


(e) Pitching moment component

Figure 16: 4/rev force and moment components of the VI metric when using the measured structural data (Ref. 12)

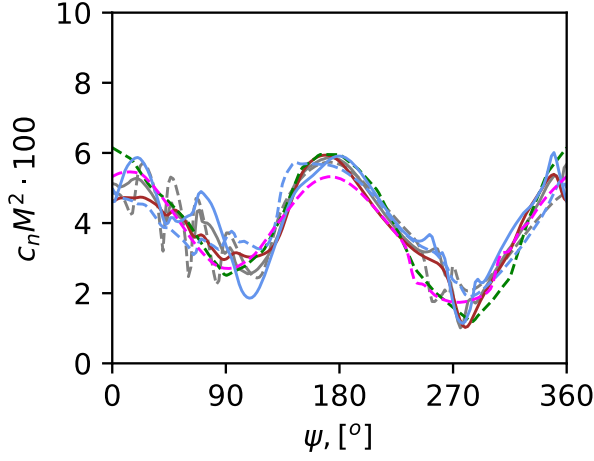


(a) $c_n M^2$

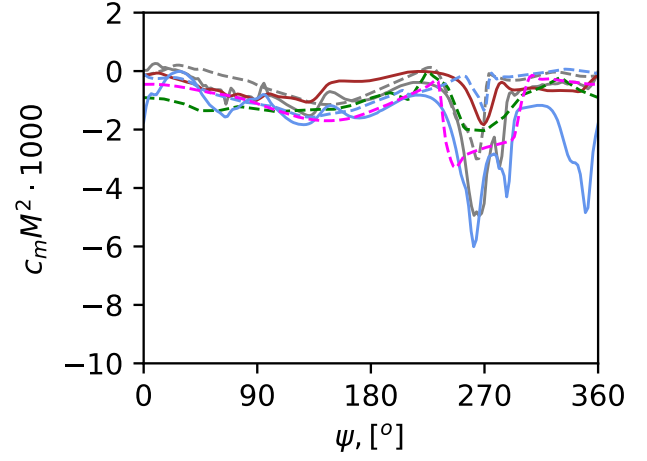


(b) $c_m M^2$

Figure 17: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.10$ with the measured structural data by Chang et al. (Ref. 12)

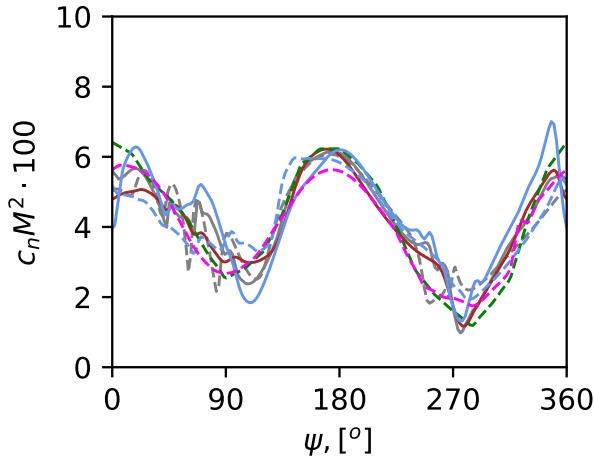


(a) $c_n M^2$

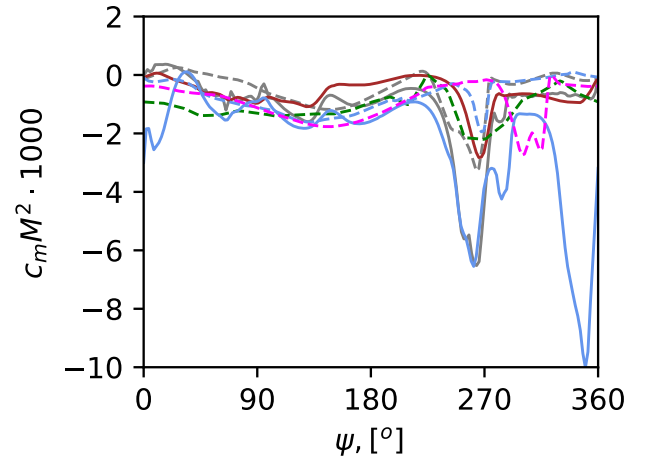


(b) $c_m M^2$

Figure 18: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.12$ with the measured structural data by Chang et al. (Ref. 12)



(a) $c_n M^2$



(b) $c_m M^2$

Figure 19: Loads at $r/R = 0.67$ for $c_T/\sigma = 0.125$ with the measured structural data by Chang et al. (Ref. 12)

is given by the vertical component $F_{z,4}$. Since ONERA-CFD correlates best here, this is also the reason for their best agreement of VI_4 . The good correlation of the $M_{y,4}$ is another reason for this fact, while the remaining components are similarly poorly predicted as for the other partners' results.

The sectional aerodynamic normal force and pitching moment at $r/R = 0.672$ cut are plotted in Fig. 17 to Fig. 19 for the thrust of $c_T/\sigma = [0.1, 0.12, 0.125]$. The experimental pressure sensor data has not been fully processed at time of this writing and is therefore excluded here. DLR-CA still predicts the strongest aft/front BVI for all thrust as previously found for the predicted structure results visible in the normal force plots. ONERA-CFD is also capturing this trend, with DLR-CFD, KARI-CFD and ONERA-CA resolving this phenomenon weakly. KU-CA is not capturing those trends. For the dynamic stall around $\psi \approx 270^\circ$, the normal force stall is moderate, whereas the pitching moment stall grows with respect to the thrust. The ONERA-CFD results indicate the strongest pitching moment stall followed by DLR-CFD, and US-CA. The pitching moment stall found by US-CA is characterized by two peaks at $c_T/\sigma = 0.12, 0.125$, whereas ONERA-CFD and DLR-CFD only have one peak. The other partners show a moderate onset. Generally, the alignment among partners remains similar as previously observed. Contrasting the low-frequency shape of the loads from the previous section with the current one, the w-shape of the normal force plots has become slightly flatter, with the pitching moment stall being a little bit more pronounced. These plots do not allow to draw conclusions on the correlation of the VI_4 metric. A small indication may be the stronger normal force variation of ONERA-CFD on the aft/advancing side $\psi = 0^\circ..90^\circ$ than the other partners leading to the stronger vertical force component.

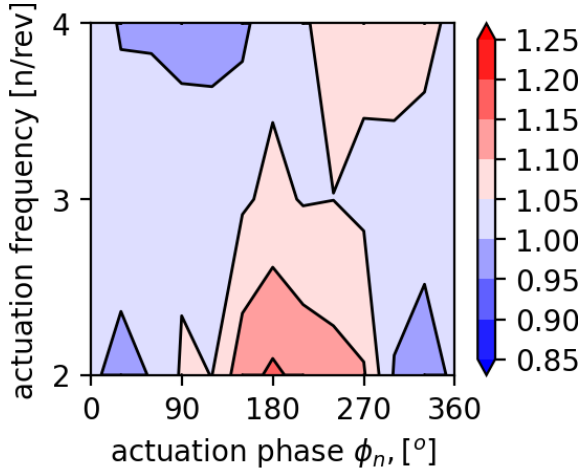
ACTUATION SWEEPS

The objective of the STAR wind tunnel campaign is to assess the feasibility of active blade twist over a wide range of operating conditions. Here, a first glance is given on the wind tunnel results and the results of the prediction team. Due to different stages of availability of simulations results, the required power and Vibration Index are normed by their respective value for the reference operational condition. This condition was changed during the wind tunnel test. Therefore, the results using the predicted structural model are referenced with the values for a thrust of $c_T/\sigma = 0.13$, whereas the wind tunnel test results along with any simulations carried with the new structural model are normed with the value for a thrust of $c_T/\sigma = 0.12$. The actuation itself is imposed through a sinusoidal signal plus an offset of pitching moment in the simulations. The amplitude of the actuation voltage is 500 V with an offset of 400 V. This is simulated as a 2.08 Nm static nose-up pitching moment with 2.6 Nm dynamical varying pitching moment and is introduced over

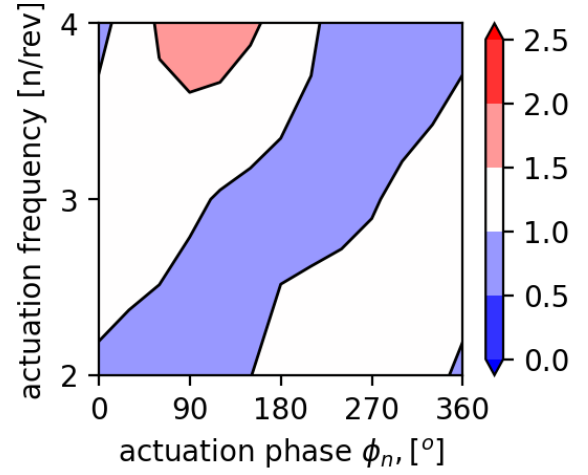
most of the airfoiled part of the blade ($r/R \approx 0.24 - 0.94$). Phase shifts have been neglected for now. A frequency dependent phase shift and frequency dependent amplitude are still under investigation by the STAR partners. The performances maps obtained from the wind tunnel data are plotted in Fig. 20. The relative required power changes are on the left, whereas on the right the changes of the Vibration Index at 4/rev are plotted. From this it is observed that for this flight condition the achievable improvements are little and mostly overshadowed by larger areas of more required power necessary than the baseline. Any additional required power for operating the actuation is neglected here, and only the pure rotor torque is considered. Conversely, for the vibrations, there are two promising areas where larger gains are found, at $(2/\text{rev}, \phi \approx 90^\circ)$ and $(4/\text{rev}, \phi \approx 300^\circ)$. The focus for the simulations activities was laid on the 2/rev simulations prior to the wind tunnel test and the point $(4/\text{rev}, \phi = 300^\circ)$ was added after the test for its optimal reduction in vibrations. Hence, partners were asked to supply data based on this priority due to the limited time between the wind tunnel test and this publication.

A more detailed comparison of the wind tunnel data with the simulations for the required power is given in Fig. 21. The quality of the simulation results varies. Focusing on the results with the predicted structural properties, the agreement for the 3/rev is captured the least, while for the 2/rev and 4/rev, DLR-CFD and KARI-CFD (single points) capture the trends fairly, with ONERA-CA as a follow-up. The KU-CA results improve significantly with the structural model for 2/rev and agree well with the experiment. KU-CFD results carried out for the prioritized data points and have very good agreement with the experiment followed by DLR-CFD. However, DLR-CFD underpredicts the required power for the front phases, with ONERA-CA on an even lower level. DLR-CA replicates mixed results with good agreement in power saving sections and over- as well as underprediction for the front phases. At 3/rev, the general gain is relatively small for the experiment, with the simulations staying in a similar magnitude. It is difficult to assess the quality based on this plot. ONERA-CA and DLR-CFD both have a kink at $\phi_3 = 270^\circ$, which is traced back to the application of the same comprehensive code and rotor model, while the aerodynamics appear to be benign enough that the aerodynamic modeling fidelity is secondary. For the 4/rev results, the approximate sign wave of the experiment is captured by all. ONERA-CA has a higher frequency response than found in the experiment. DLR-CA agrees well for the aft/advancing side phase and overpredicts the front/retreating side phase the most. KU-CA is closest to the experiment, while DLR-CFD has a reduced amplitude of the signal with KARI-CFD aligning with DLR-CFD at $\phi_4 = 300^\circ$.

The 4/rev Vibration Index is plotted in Fig. 22. The general spread of the simulations is large and is not significantly reduced when the measured structural model is



(a) Relative required power $c_p/c_{p,ref}$



(b) Relative 4/rev Vibration Index $VI_4/VI_{4,ref}$

Figure 20: Performance maps of the DNW-Experimental wind tunnel data

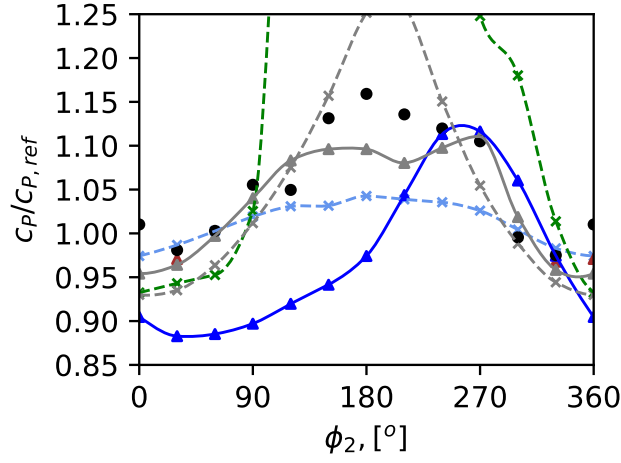
used instead of the predicted one. For the 2/rev simulations with the predicted structural model, DLR-CA captures the sine-wave trend with a large overprediction of the trend past $\phi_2 > 180^\circ$, whereas ONERA-CA and DLR-CFD have a good agreement. The KARI-CFD results are very close to the JAXA-CFD results except for $\phi_2 = 300^\circ$ where they align with DLR-CFD and the experiment. At 3/rev, DLR-CFD and ONERA-CA obtain good results for the aft/advancing phase angles and DLR-CA for the retreating side angles. The 4/rev results with the predicted structural data capture the trend fairly with all partners resolving a dip around $\phi_4 \approx [180^\circ..270^\circ]$ and a sharper recovery than the experiment. Looking at the simulations with the measured structural data, DLR-CFD has a fair to good agreement for all frequencies with KARI-CFD confirming the results on the retreating side. The largest discrepancy is at $\phi_3 = 240^\circ, 270^\circ$ as a bump, while at 4/rev, the offset of the advancing side grows largest. ONERA-CA captures the trend of the 2/rev actuation reasonably, but show strong deviations for the other two frequencies. US-CA is close to the experiment at three 3/rev and shows a phase shift of roughly $\Delta\psi \approx 60^\circ$ to the experiment at 4/rev with and approximated phase shift of $\Delta\psi \approx -60^\circ$ for the 2/rev simulations. DLR-CA also replicate the 3/rev results well with respect to the experiment, while for the other frequencies additional peaks are found that are not present in the experiment.

CONCLUSIONS

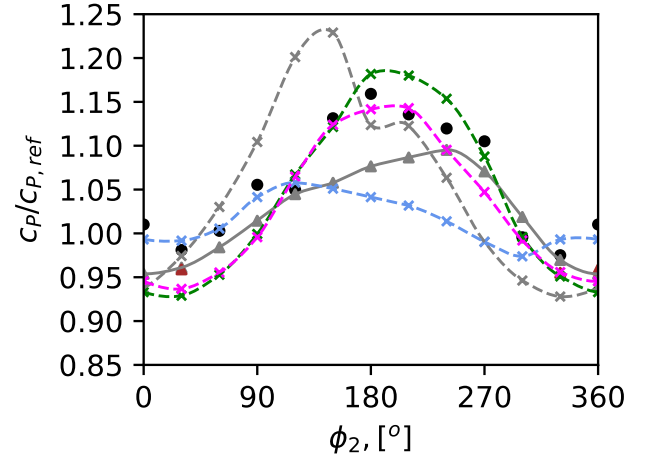
This paper presents the Smart Active Twisting Rotor (STAR) high load wind tunnel results for the first time, where the rotor has been operated with and without actuation. These are contrasted to the various prediction team activities. The methodology section shows that partners had a great variety in their simulation setups,

ranging from comprehensive code neglecting the fuselage and terminal box of the blade root section to CFD/CSD coupled results with scale resolving capabilities including both components. The simulations results have been presented in four sections:

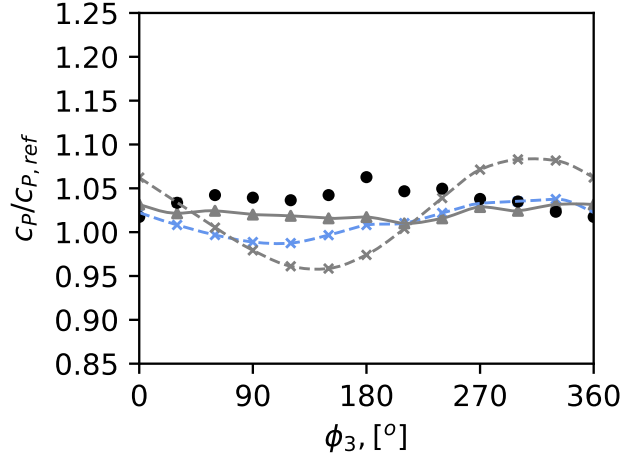
1. A preliminary study investigating the impact of grid resolution for the unactuated blade. The outcome was that a certain grid dependency exists, but when higher order, low dissipation schemes are available, grids in the order of tenth of million cells are reasonable and a background grid spacing around $\Delta x/c \approx 10 - 15\%$ is a good economic choice.
2. Results presented prior to the wind tunnel test (Ref. 11), but also prior to the availability of measured structural properties of the blade (Ref. 12) have been contrasted with the experimental data now for the unactuated rotor. As expected from the methodology section, there was a fair variation of simulation results. CFD based approach and carefully tuned comprehensive code simulations aligned well with the experiment and replicated the values of the control angles and required power well. The prediction of vibrations has mostly been poor with the exception of CFD results produced by JAXA-CFD that have a good agreement with the experiment.
3. The adoption of the measured structural properties but also availability of the wind tunnel data allowed for more adjusted simulation results. The agreement with the experiment was improved for most partners for the unactuated rotor, in particular ONERA-CFD results correlate best with the experiment. Nevertheless, the prediction of vibrations was mostly poor. However, inspecting the individual components contributing to the vibration metric revealed that this



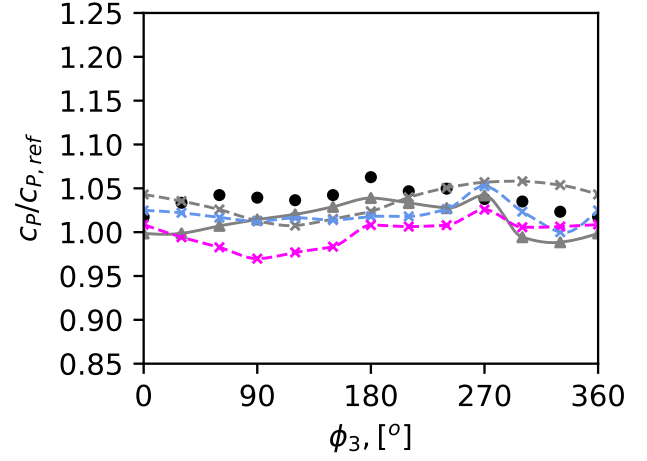
(a) simulations using the predicted structural data



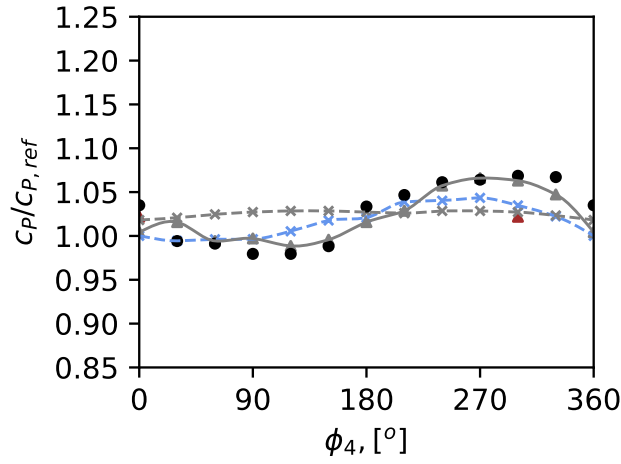
(b) simulations using the measured structural data



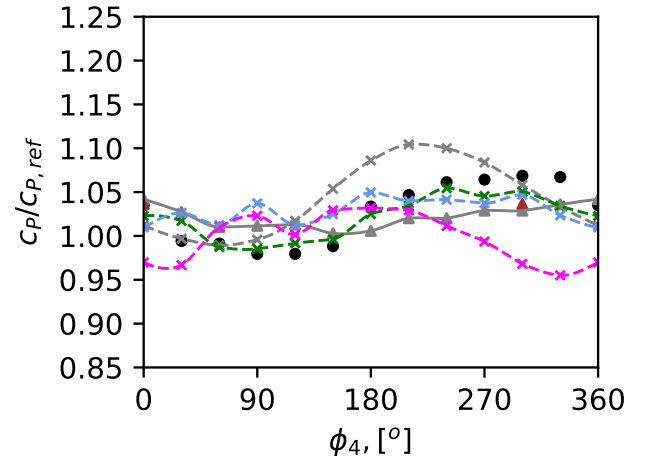
(c) simulations using the predicted structural data



(d) simulations using the measured structural data

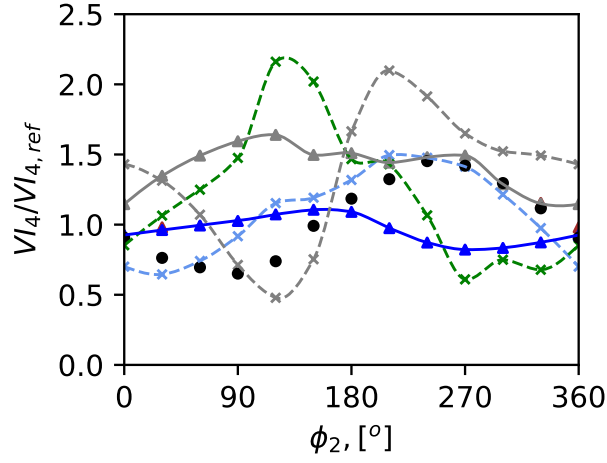


(e) simulations using the predicted structural data

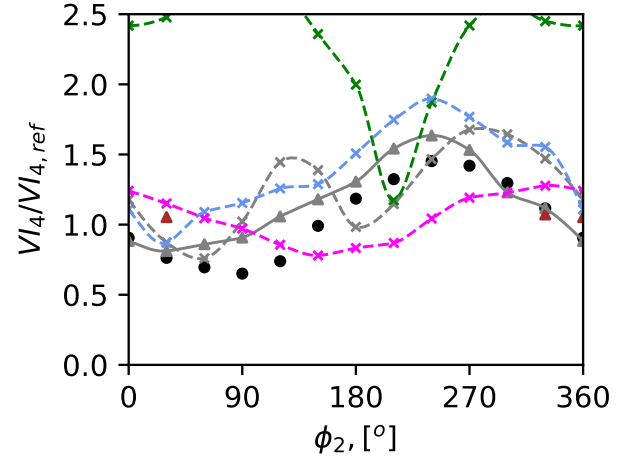


(f) simulations using the measured structural data

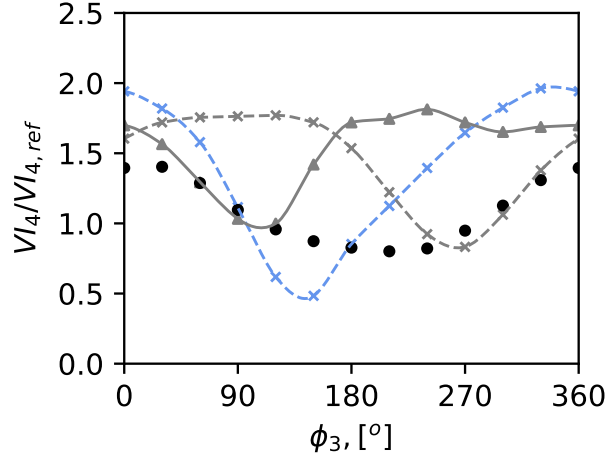
Figure 21: relative required power for 2, 3 and 4/rev actuations



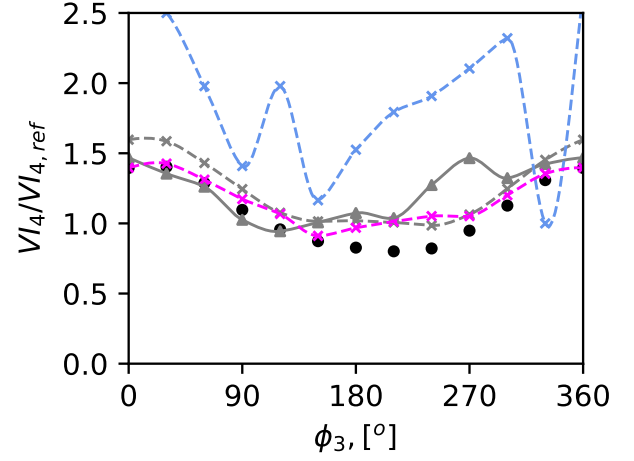
(a) simulations using the predicted structural data



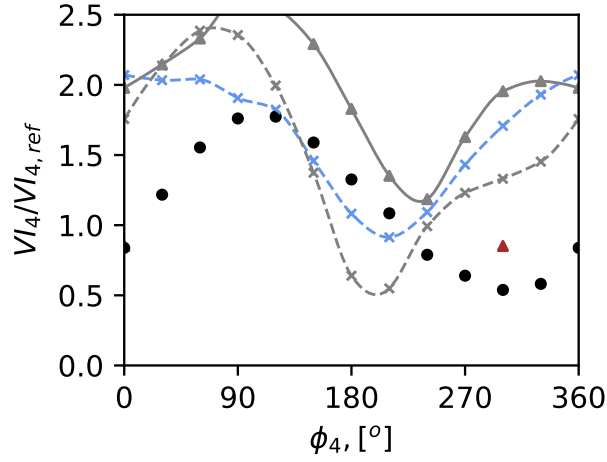
(b) simulations using the measured structural data



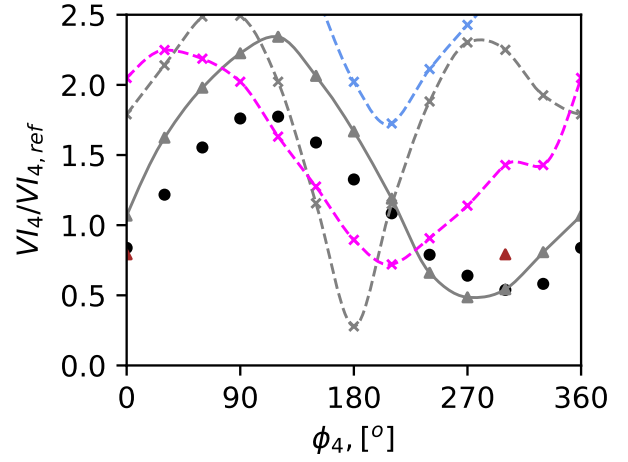
(c) simulations using the predicted structural data



(d) simulations using the measured structural data



(e) simulations using the predicted structural data



(f) simulations using the measured structural data

Figure 22: relative 4/rev Vibration Index at 2, 3 and 4/rev actuations

is generally challenging and should become a topic for future simulation improvements.

4. The application of the actuation of the rotor demonstrated more possibilities to increase the required power than to reduce it already excluding any additional required power for the actuation. On the other hand, the vibrations could be reduced by up to 42% in the experiment using the blade actuation. These improvements have then been computed for the simulations relative to the baseline thrust. The agreement of the power predictions with the experiment was mildly improved with the new structural model, while the vibration prediction remained challenging. Here DLR-CFD benefitted the most from the new structural properties and revealed a fair to good agreement with the experiment for the actuated cases.

Besides the direct observations found from the results sections, it is further concluded:

- The application of comprehensive codes appears to yield more diverse results. Partners that used the same comprehensive code generated very different results. KU-CA was mostly in the better half of comprehensive code predictions, whereas US-CA results were of lower quality, despite the fact that both partners used CAMRAD II. Conversely, once results were CFD coupled, results between partners moved closer together, even though the choice of potential parameters of CFD codes is likely exceeding the number of numerical options of comprehensive codes.
- The change of results between the predicted and measured structural data had a much larger impact than changing CFD grid size. While the CFD results always benefit from improved spatial and temporal resolutions, it appears that the blade dynamics may need further improvement. However, this is a hypothesis to be proven by future work. Other sources of error may include the neglect of the wind tunnel walls, the nozzle, proper rotor head modeling, but also a more in-depth simulation of the actuation beside a plain momentum application to the blade.

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and Culture of Lower Saxony" and "Federal Ministry of Research, Technology and Space".

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The ONERA CFD simulations were performed using the CFD solver elsA (ONERA-Safran property).

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