Journal of Physics: Conference Series

PAPER • OPEN ACCESS

VAST as a generic, modular aeromechanics code for wind turbine simulation

Journal of Physics: Conference Series **2767** (2024) 052023 doi:10.1088/1742-6596/2767/5/052023

VAST as a generic, modular aeromechanics code for wind turbine simulation

Benedikt Michels[1] **and Philipp Seelemeyer**[2]

German Aerospace Center, [1] Institute of Flight Systems, [2] Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, DE

E-mail: `Benedikt.Michels@dlr.de, Philipp.Seelemeyer@dlr.de`

Abstract. In order to leverage the full potential wind energy, more research is needed both in the field and numerically. At DLR, the need for simulation competencies is expected to be met by the in-house developed generic and highly flexible multi-physics code VAST. While initially aimed at low- to medium-fidelity simulations of helicopter aeromechanics, the code is applicable to other problems like wind turbine computations. The goal of this paper is to present the general concept of VAST and briefly introduce the available physics models. Next to examples of successful application to helicopter simulation problems, first results in the field of wind energy are shown. The well-known IEA 15 MW reference wind turbine is used as a basis to compare VAST — both with a BEMT and a vortex theory inflow model — to other tools with similar and higher-fidelity physics modeling. For the rigid turbine, blade loads are compared with results of other tools using engineering models as well as CFD, showing good overall agreement. A more detailed evaluation of aerodynamic quantities like the angle of attack and the induced velocity field is presented for VAST and the CFD results. An outlook on the ongoing VAST developments is given.

1. Introduction

One big challenge in fighting climate change is the reduction of the carbon footprint of power generation. Wind already serves as a renewable energy source at big scale, but open questions e.g. in improving the efficiency of wind energy extraction remain.

In a joint effort, the Research Alliance Wind Energy (German Aerospace Center DLR, Fraunhofer Institute for Wind Energy Systems IWES and ForWind — the Center for Wind Energy Research of the Universities of Oldenburg, Hanover, and Bremen) addresses some of these, by means of the new research wind farm WiValdi (Wind Validation) [1]. It consists of two commercial, multi-megawatt wind turbines which are placed in close proximity to each other, to also allow for investigation of wake interaction effects. Besides the heavily instrumented turbines, several meteorological masts have been installed to measure the flow conditions in front of and behind the turbines. A third, smaller turbine is planned to be erected downstream in main wind direction.

In order to fully leverage the potential of the research wind farm, in-house modeling capabilities are deemed essential. Of the various fidelity levels, this paper will focus on fast engineering models, commonly used e.g. for performance prediction, loads calculation for structural design, prediction of the aeroelastic behavior or controller design and evaluation. Having the software tool development competencies then allows to react to specific simulation needs, e.g. arising from future unconventional turbine configurations. Apart from the inherent benefits of in-house development competencies, some limitations of existing, well-established tools drive the need for the herein presented code.

While the multi-physics solver OpenFAST [2], developed by the US National Renewable Energy Laboratory and widely used by the research community, offers a broad range of applications from structural analysis over aerodynamics and hydrodynamics to control, it is limited to horizontal axis wind turbines (HAWT). Therefore, the recent extension of the OpenFAST aerodynamics module AeroDyn for the simulation of arbitrary collections of wings, rotors, and towers [3] still lacks coupling with the structural modeling. DNV's wind turbine design software Bladed [4], often used e.g. for certification simulations, is similarly aimed at HAWT exclusively. Multiple rotors are supported in the structural and multi body modeling, but with some limitations: The rotors have to be identical, and aerodynamic interactions between the different rotors are not considered. Other existing tools face similar shortcomings in the flexibility of modeling non-standard configurations.

2. VAST - Versatile Aeromechanics Simulation Tool

VAST is a comprehensive tool, one of the aims of which being the interdisciplinary simulation of wind turbines. It is targeted at different application scenarios, ranging from pre-design of novel configurations over loads analysis and controller evaluation wake interaction studies for closely spaced turbines. For non-commercial use, a license agreement covering the free of charge provision of VAST as source code and binary is available for universities and research institutions.

VAST development in general

Initially, the VAST development started in the rotorcraft research field, with some similarities to the above-mentioned simulation goals. Here it is aimed e.g. at conceptual and pre-design, flight mechanics and real-time flight simulators, but also coupling with high fidelity methods and detailed aeromechanic simulations. In existing codes with similar goals, assumptions concerning the vehicle configuration are made very often, limiting the applicability of such tools e.g. to typical main-rotor/tail-rotor configurations. Furthermore, assumptions about the operating conditions, e.g. a constant rotor speed, prohibit certain use cases, in this case for example the investigation of rotor-drivetrain coupling.

In the following, only a short overview of the approach chosen in VAST will be given. A more detailed description of VAST can be found in [5].

In order to allow for more versatility and flexibility, the physical system to be simulated is represented by a coupled system of models in state-space form, possibly of different fidelity levels. The solver can be agnostic of the physics modeling in the individual models, which only have to comply with a common interface, defined by inputs, outputs and, optionally, states. Mapping between input and output happens automatically based on variable naming, units, and dimensions. Doing so, generic solving strategies can be applied to the resulting system of equations. A schematic of the VAST system is given in figure 1.

The user input, meaning the selection and configuration of the physical models as well as the definition of simulation tasks is done using an `xsd`-validated (xml schema definition) `xml` (extensible markup language). The graphical user interface (GUI) allows defining the system, setting up and running simulation tasks as well as post-processing and visualizing the results.

Applicability and adaptation for wind energy

Thanks to the generic and versatile approach, VAST lends itself well to wind turbine simulation, offering substantial synergies arising from existing modeling and validation effort in the helicopter field. The integrated multi-body system (MBS) already allows for a representation of the rigid-body kinematics and dynamics, while the capabilities for flexible bodies are currently

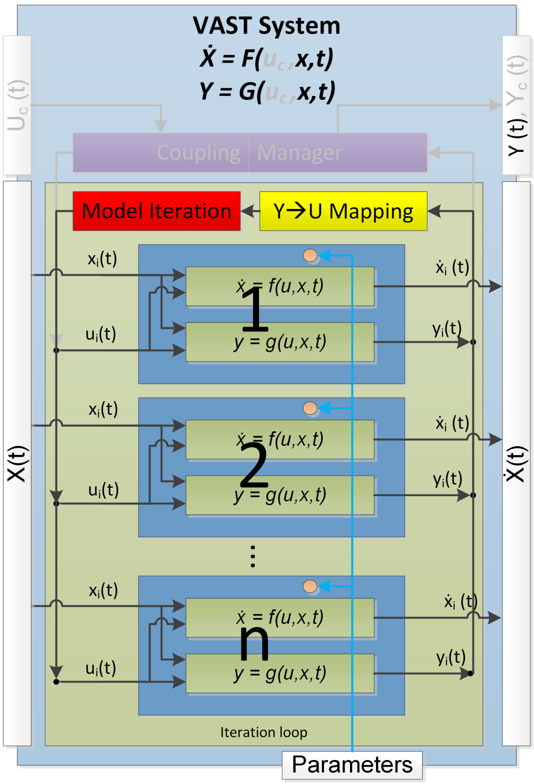

Figure 1. The VAST system, consisting of one to n models in state-space formulation. Each model implements the dynamics equation $\dot{x} = f(u, x, t)$ as well as the output equation $y = g(u, x, t)$, with x being the state(s) and $\dot{x}$ the state derivative(s), u the input(s) and y the output(s) of the model. After mapping the global output vector to all model inputs, the system is iterated by the solver. Taken from [5].

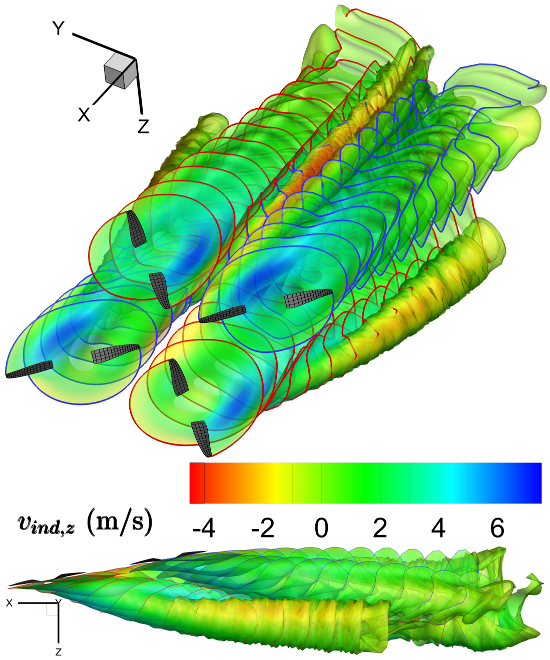

Figure 2. Visualization of the VAST-Freewake simulation of a quadrotor in forward flight, showing the blade grid and the wake shape, with the z-component of the induced velocity $v_{ind,z}$ as contour variable. Unpublished results of a validation study of the VAST-Freewake aerodynamics for different quadrotor configurations, using the experiment by Kostek et al. [6].

being developed. Alternatively, a well-tested coupling to the commercial MBS tool Simpack can be used. Furthermore, various aerodynamics models and modeling options are available. Loads on rotor blades or wings can be computed using either a linear airloads model, tabulated airfoil polar data or a semi-empirical analytical model [7]. Different modeling approaches for different, arbitrarily chosen radial sections can be combined and are linearly interpolated. A blade geometry module allows for the generic definition of a rotor blade or wing, by specifying the distribution of the local chord length, offsets in flapwise and lead-lag direction as well as twist, sweep, and dihedral angles. The discretization into blade elements for the simulation follows in a subsequent step and is independent of the geometry and airfoil definition locations, thus can be freely altered. Inflow models of different fidelity levels are available, too, ranging from global models like Glauert [8] (steady) or Pitt-Peters [9] (unsteady) over localized models like blade element momentum theory (BEMT, steady) and a generalized dynamic wake [10] (GDW, unsteady) up to a free-wake vortex lattice model [11]. While the BEMT model was specifically added for wind turbine applications, the existing free-wake model is also well suited for wind turbine applications thanks to its implicit approach. The free-wake model supports modeling both rotor blades and wings with arbitrary motion given by the MBS. Furthermore, interactions between multiple lifting surfaces, even of different turbines or vehicles, can be directly accounted for. An example for the VAST-Freewake simulation of a quadrotor configuration is given in figure 2. The BEMT implementation in VAST makes use of the proposal by Buhl [12] to incorporate the tip loss factor into the dependency between thrust coefficient and induction factor in turbulent windmill state. Further models cover e.g. aerodynamic loads on the fuselage, empennage or a tail rotor, or, in a simplified manner, interference effects between components.

Additionally, more wind-turbine specific models are currently under development. As of now, a model for the tower dam effect is available, offering interference velocities according to potential flow theory as well as the formulation based on the work by Bak [13], incorporating the tower drag coefficient. In contrast to the commonly found implementations of this approach, VAST avoids the discontinuity when a blade element marker passes the hub height. Instead of the non-physical switch-like behavior of the tower dam effect at this height, a smoothing function has been introduced. Wind input can be processed either as a global uniform wind velocity vector given in the configuration, or read in from user-provided files. For now, two file formats are supported, the definitions of which can be found in [14]:

- Non-turbulent parameterized "Hub-Height AeroDyn formatted" ASCII
- "Full-Field BLADED-Style" binary

Examples of successful applications of VAST using some of the aforementioned capabilities can be found in the literature: In [15], the coupling of the VAST aerodynamics models with Simpack is used to demonstrate the simulation of a free flying helicopter, while in [16] a VAST-Simpack-Matlab coupling is used to investigate loads on hingeless helicopter rotors including drivetrain dynamics.

Comparison codes

- *TAU*: The well-established in-house CFD code TAU [17] solving the RANS equations is used for comparison with the lower-fidelity methods employed in VAST. The setup contains an isolated rotor and neglects shaft tilt and yaw, but uses the cone angle from the rotor description. For the steady RANS simulation the k-ω-SST turbulence model is used. The discretization is performed using overset grids with a total of 5×10^7 cells, where the rotor disc is embedded in a separate refinement block as well as each individual blade. The farfield extends up to 10 radii in and against flow direction. The dimensions of the rotor disc refinement block are designed to provide high resolution for the wake of one rotor revolution. The O-type cylindrical blade grids are created with a script-based approach that allows for fully structured and consistent quality mesh resolution close to the blade surface.
- *Bladed-FVW* [4], *NREL-OLAF* [3],[18], *TNO-AWSM* [19]: Free vortex wake based simulation methods, the results of which have been kindly provided by DNV-GL, NREL and TNO.

3. Wind turbine model description and simulation setup

First wind turbine simulations with VAST are performed using the well known IEA 15 MW reference wind turbine [20] (RWT). The three-bladed upwind turbine has a rotor diameter of 240 m and a hub height of 150 m. The simplest commonly used simulation case includes a rigid configuration of the turbine without shaft tilt, operating at prescribed constant values for pitch and rotor speed in homogeneous wind of ($7.5\,\mathrm{m\,s^{-1}}$). The setup is then extended by adding shaft tilt and taking into account the aerodynamic effects of the tower. A graphical representation of the blade geometry of the untilted turbine without tower in the VAST GUI is shown in figure 3. Note that the airfoil shape representation is given by a fixed set of coordinates for the whole radius only scaled by the local chord for now, which is why there is no circular cross-section to be observed near the blade root. This limitation stems from the helicopter origins of VAST where airfoil shapes typically do not change dramatically with radius, and only affects the graphical representation. A screenshot of the model tree view is shown in figure 4. The tree is partially expanded to give a general overview of the models involved, but also to show some details about the individual model configuration choices. In the present case, the system consists of structure and aerodynamics models only. Further options include e.g. control, actuator or propulsion models.

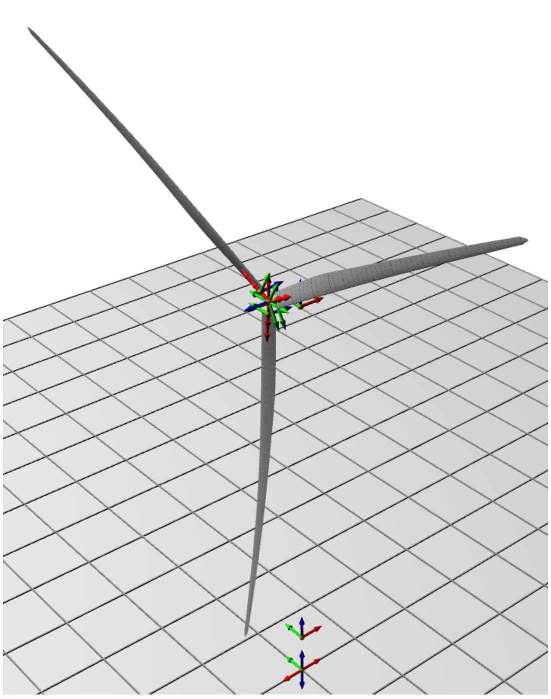

Figure 3. 3D-view of the IEA 15 MW reference wind turbine in the VAST GUI, blade 1 pointing down at an azimuth angle of 180°.

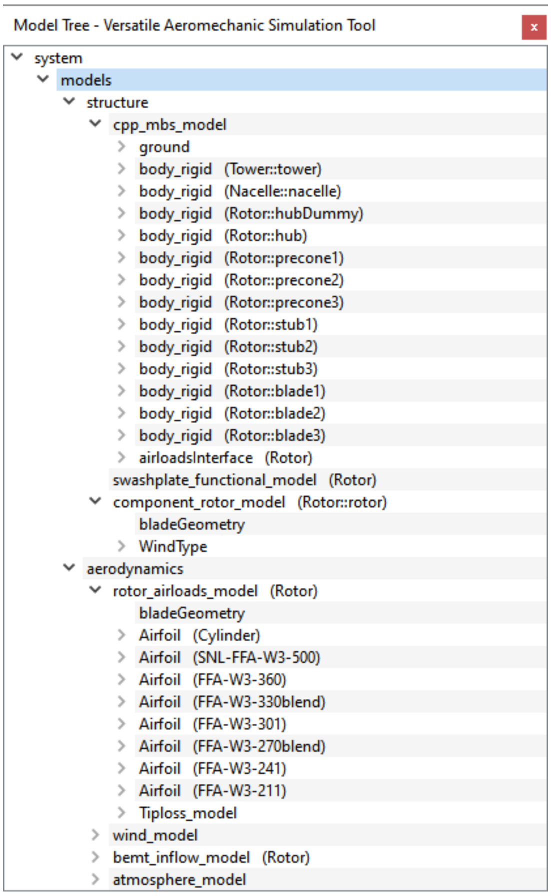

Figure 4. Partially expanded model tree view of the IEA 15 MW reference wind turbine configured in the VAST GUI.

4. First results

Baseline without shaft tilt, no tower dam effect First results are obtained for the simplest simulation case defined in the IEA TASK 37. The rigid, untilted turbine is operated at a constant uniform wind speed v_{Wind} of $7.5\,\mathrm{m\,s^{-1}}$, a constant rotor speed ω of $0.558\,\mathrm{rad\,s^{-1}}$ (or $5.33\,\mathrm{min^{-1}}$) and a fixed pitch of 0°. All VAST computations shown here use a discretization of 50 equidistant blade elements, as this proves to be a good compromise between computation time and accuracy, especially for the more computationally demanding Freewake inflow model.

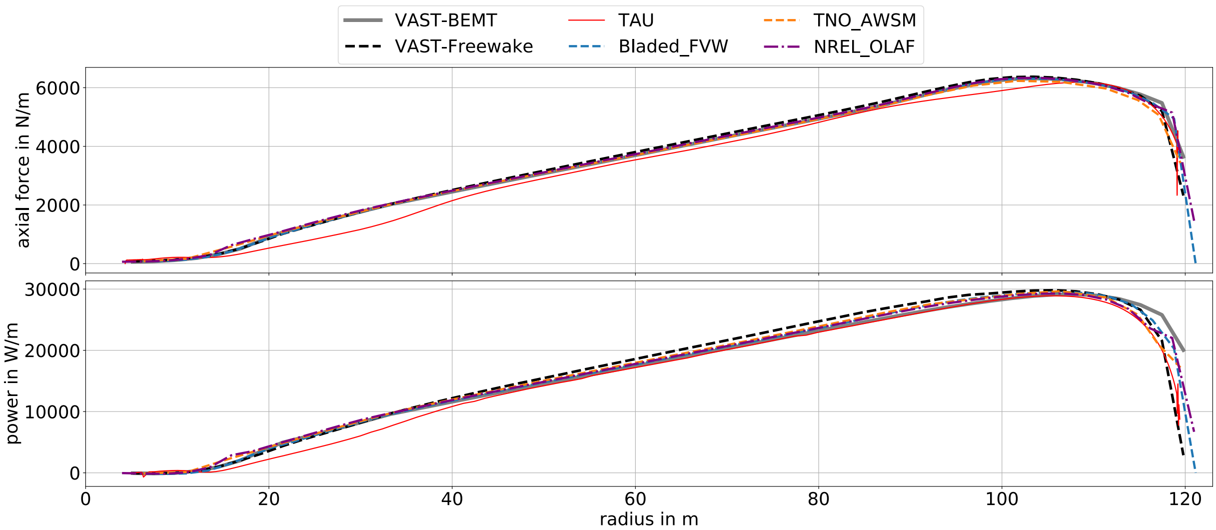

Figure 5. Radial distribution of axial force and power per unit length for the baseline IEA 15 MW case without tilt, at $7.5\,\mathrm{m\,s^{-1}}$.

These settings result in roughly real-time performance on a laptop for the simpler BEMT inflow model. The VAST-Freewake calculation runs significantly slower at about 30 times real-time on a 64-core workstation, still yielding acceptable computation times though. Figure 5 shows the resulting radial distribution of axial force (thrust) and power per unit length for all presented codes for the simplest simulation case.

The agreement between the newly presented VAST code using the Freewake inflow model and the other vortex-theory based methods is good, both in thrust and power. For reference, results from VAST using the simpler BEMT inflow model are included as well. These show only little deviations in the general prediction behavior, but exhibit some differences towards the blade tip, where explicit modeling of the tip loss via the Prandtl function is opposed to the implicit modeling employed in the vortex codes. The CFD results from TAU also match well overall, although being shifted to slightly lower values overall. Locally, they also exhibit some qualitative differences, most prominently visible inboard between 20 m and 40 m radius. Here TAU predicts a flow separation, which leads to a slight drop in thrust and power.

In order to further investigate the differences with CFD, the local flow conditions are examined in more detail. The local aerodynamic angle of attack (AoA) is chosen as another means of comparison, as it provides valuable insights into the local flow behavior. While the AoA is a direct result of the blade element momentum calculations, accurately determining this angle in a three-dimensional CFD turbine simulation can be challenging. The curved flowfield around each blade causes the evaluation of the inflow direction to vary depending on the chordwise and normal distance along each airfoil section. To ensure physically accurate and consistent readings of the local aerodynamic AoA across different radial stations, the annulus ring induction method developed by Hansen was used [21]. A radial discretization of 1 m was chosen to extract AoA data.

The resulting data is shown in figure 6 for both VAST and TAU. For reference, VAST-BEMT results are included as well. Additionally, the AoA for maximum lift ($C_{L,max}$), extracted from the tabulated airfoil polars used in VAST, are shown. When comparing the data with the resulting forces and moments (fig. 5), it has to be noted that identical AoA for VAST and TAU do not have to lead to identical aerodynamic forces. VAST retrieves forces and moments from pre-computed two-dimensional airfoil lookup tables, whereas TAU directly computes the possibly three-dimensional flow on a volume mesh.

Overall, the AoA predictions between VAST and TAU match quite well, especially in the region between 60 m and 110 m. The differences at the blade tip can most likely be attributed to the different modeling approaches. While the blade aerodynamics essentially stay two-dimensional in VAST due to the blade element approach, TAU captures the three-dimensional flow field at the blade tip. Something similar holds true for the deviations inboard between 10 m and 40 m. The above-mentioned local flow separation in TAU, visible through the reduced load compared to the non-CFD codes (cf. fig. 5), leads to less deceleration of the oncoming flow, and therefore a higher angle of attack. Only for radial stations closer than 20 m to the blade root, the VAST-predicted values are close to or above the tabulated AoA of maximum lift, indicating possible flow separations. Additionally, VAST does not use any rotational augmentation corrections yet on the airfoil polars, while in TAU the effects are implicitly covered, giving further reason for the differences inboard. Further outboard, the predicted AoA are well in the linear regions of lift polars.

Figure 7 shows a comparison of the x-velocity field around the turbine for VAST-Freewake and TAU. As the BEMT model does not provide induced velocities outside of the rotor plane, this model is not included in the comparison. For convenience, the hub position has been moved to $x = z = 0$ m. The rotor azimuth is identical for both codes, having the first blade pointing upwards at $\psi = 0°$. The flow deceleration in front of the turbine is predicted very similarly by the two codes, with small differences only in front of the rotor center. This is due to the different modeling choices: While TAU models the hub body and the blade attachments, the flow in VAST-Freewake can freely pass the root cutout area and therefore undergoes a lot less deceleration. The tip vortex-induced velocities are also rather similar directly behind the blade tip, both qualitatively and quantitatively. This changes further downstream, because the CFD simulation is more dissipative than the Freewake approach, leading to quickly disappearing tip vortices. This also affects the velocity recovery behind the blade mid-section. Similar to the behavior in front of the rotor center, the velocity field behind it differs due to the missing hub effect in VAST-Freewake.

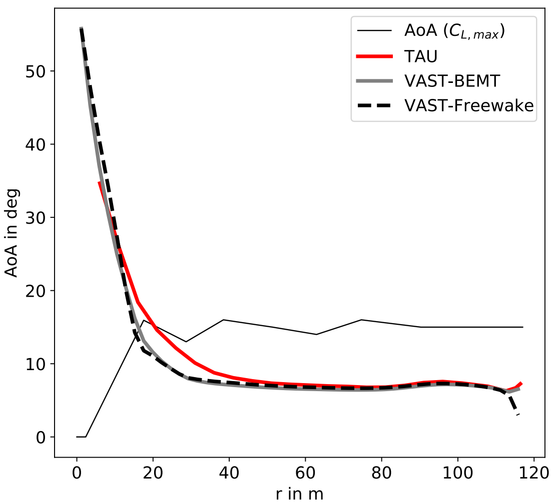

Figure 6. Distribution of the angle of attack for VAST-BEMT, VAST-Freewake and TAU along the blade span. For reference, the angle of attack for maximum lift from the tabulated airfoil polars is shown as well.

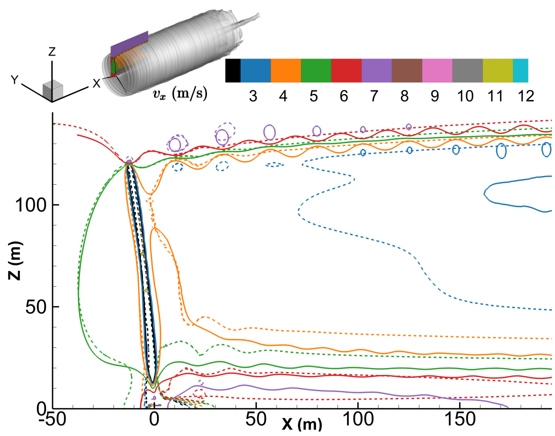

Figure 7. Comparison of the x-velocity (v_x) field around the turbine. VAST-Freewake: solid lines; TAU: dashed lines.

Journal of Physics: Conference Series **2767** (2024) 052023 doi:10.1088/1742-6596/2767/5/052023

Inclusion of shaft tilt and tower dam effect In the more complex simulation case with a shaft tilt of 6° and inclusion of the tower dam effect, the lift coefficients vary azimuthally, as shown in figure 8. Tilting the shaft results in a shift of AoA. Consequently, the lift coefficients are slightly higher on the upstroke of the blade (left half of the polar contour plot). Furthermore, the flow deceleration in front of the tower leads to a reduction of both the AoA and the dynamic pressure, which results in decreased lift around an azimuth angle of 180°. Capturing this lift variation is essential, especially for controller design and loads prediction in case of a simulation with flexible blades (and tower).

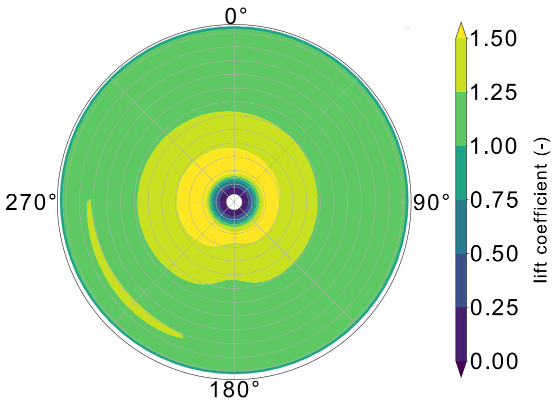

Figure 8. Azimuthal and spanwise distribution of lift coefficient for VAST, for the IEA 15 MW case with shaft tilt and tower blockage, at 7.5 m s^{-1}, looking downwind.

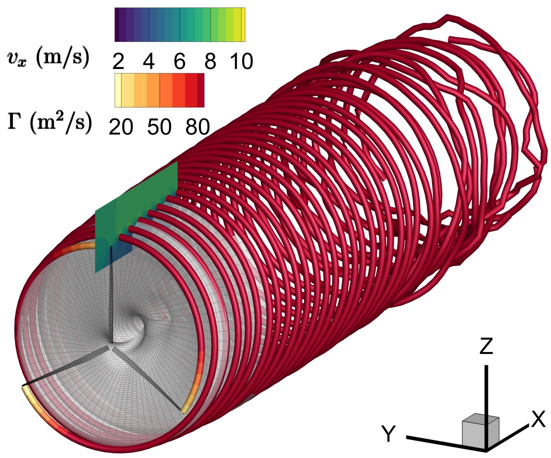

Figure 9. Visualization of the Freewake, showing the tip vortex tubes colored by the circulation Γ, the wake grid for blade one as well as the x-velocity v_x in a plane cutting through the tip vortices.

The wake resulting from the VAST-Freewake computation given the above setup is shown in figure 9. Besides the blade and wake grid, also the resulting tip vortex tubes are depicted. The contour color is given by the circulation level, showing the effect of the explicitly modeled tip vortex roll-up. Within an azimuth range of about 40°, circulation from the outermost part of each blade's wake is concentrated into a single tip vortex. The wake helix remains stable for several revolutions, before beginning to oscillate. In reality, the decay would occur earlier due to atmospheric turbulence and vortex diffusion. Another source of instability is the tower dam effect, which leads to a variation in circulation with azimuth which is proportional to the blade loading. This is even though the tower itself is not modeled in Freewake directly, but only affects the blade aerodynamics. Furthermore, the possibility to extract induced velocities at arbitrary points in space is demonstrated in the figure with the x-z-plane, showing the x-component of the velocity.

5. Conclusion and Outlook

The general applicability of the VAST aerodynamics modeling to wind turbine simulation problems has been shown. While some models or model extensions are still missing for more complex simulation cases, the results for the simpler cases match well with those of established simulation codes of similar fidelity. The comparison to CFD shows a good agreement, too, with some expected deviations due to the entirely different modeling approaches. Current activities focus on the setup of a flexible turbine model in VAST as well as in the Simpack-VAST coupling.

This will allow investigating the effects of flexibility on the blade aerodynamics, as well as a code-to-code comparison of the flexible structural modeling in VAST and Simpack. Furthermore, an extension to allow for the aerodynamic and structural modeling of trailing edge flaps is currently being worked on. Further research is planned in combination with the new research wind farm. This will involve transitioning from the generic IEA 15 MW RWT to the actual turbines used in the field, and making use of measured wind data for more extensive validation, both of the directly rotor-related quantities as well as the wake.

Acknowledgments
The authors kindly appreciate the provision of vortex code result data for the IEA 15 MW RWT by Galih Bangga, Emmanuel Branlard and Koen Boorsma. Furthermore, the authors wish to thank Lea Schmitt and Philipp Kunze for providing VAST-Freewake results of the quadrotor validation study.

References

[1] Research Alliance Wind Energy, "Krummendeich Research Wind Farm WiValdi," https://www.windenergy-researchfarm.com, 2023, Accessed: 2023-12-29.

[2] Jonkman, B., Platt, A., Mudafort, R. M., Branlard, E., Sprague, M., Ross, H., Jonkman, J., Hayman, J., Slaughter, D., Hall, M., Vijayakumar, G., Buhl, M., Russell, A. J., Bortolotti, P., Crozier, R., Ananthan, S., Davies, R., , Rood, J., Damiani, R., Mendoza, N., Long, H., Schuenemann, P., Sharma, A., Shaler, K., Housner, S., Sakievich, P., Wang, L., Bendl, K., and Carmo, L., "OpenFAST/openfast: v3.5.2," https://zenodo.org/doi/10.5281/zenodo.10530537, Jan. 2024.

[3] Branlard, E., Brownstein, I., Strom, B., Jonkman, J., Dana, S., and Baring-Gould, E. I., "A Multipurpose Lifting-Line Flow Solver for Arbitrary Wind Energy Concepts," *Wind Energy Science*, Vol. 7, No. 2, 2022, pp. 455–467. 10.5194/wes-7-455-2022.

[4] DNV GL, "Bladed Wind Turbine Design Software," https://www.dnv.com/services/wind-turbine-design-software-bladed-3775, 2023, Accessed: 2023-12-29.

[5] Hofmann, J., Weiss, F., and Mindt, M., "A New Approach to Comprehensive Rotorcraft Aeromechanics Simulation," *VFS 77th Annual Forum*, Online, May 2021.

[6] Kostek, A. A., Braukmann, J. N., Lößle, F., Gardner, A. D., Riziotis, V., Miesner, S., Keßler, M., Visingardi, A., and Boisard, R., "Experimental Investigation of Quadrotor Aerodynamics with Computational Cross-Validation," *Vertical Flight Society 79th Annual Forum & Technology Display*, West Palm Beach, Florida, USA, May 2023. https://doi.org/10.4050/F-0079-2023-17991.

[7] Mindt, M., "Merging an Analytical Aerodynamic Model for Helicopter Applications with a State-Space Formulation for Unsteady Airfoil Behavior," *67. Deutscher Luft- und Raumfahrtkongress*, Friedrichshafen, Germany, Sep. 2018.

[8] Glauert, H., *Aerodynamic Theory*, chap. Airplane Propellers, Springer, Berlin, Heidelberg, 1935, pp. 169–360. https://doi.org/10.1007/978-3-642-91487-4_3.

[9] Pitt, D. M. and Peters, D. A., "Theoretical Prediction of Dynamic-Inflow Derivatives," *Vertica*, Vol. 5, No. 1, Jan. 1981, pp. 21–34.

[10] He, C., *Development and Application of a Generalized Dynamic Wake Theory for Lifting Rotors*, Phd thesis, Georgia Institute of Technology, 1989.

[11] van der Wall, B. G. and Roth, M., "Free-Wake Analysis on Massively Parallel Computers and Validation with HART Test Data," *53rd Annual Forum of the American Helicopter Society*, Virginia Beach, VA, USA, May 1997.

[12] Buhl, Jr., M. L., "A New Empirical Relationship between Thrust Coefficient and Induction Factor for the Turbulent Windmill State," Tech. Rep. NREL/TP-500-36834, National Renewable Energy Laboratory, Aug. 2005.

[13] Moriarty, P. and Hansen, A., "Aerodyn Theory Manual," Tech. Rep. NREL/TP-500-36881, National Renewable Energy Laboratory, Jan. 2005.

[14] Jonkman, B. J., "TurbSim User's Guide," Tech. Rep. NREL/TP-500-46198, National Renewable Energy Laboratory, Sep. 2009.

[15] Mindt, M., Dietz, S., Schulze, M., and Mabou, H., "Simulation of the Free Flying Helicopter by Coupling of a New Comprehensive Aeromechanics Code with an Advanced Flexible Multibody Model," *Vertical Flight Society 75th Annual Forum & Technology Display*, Philadelphia, PA, USA, May 2019. https://doi.org/10.4050/F-0075-2019-14570.

[16] Weiss, F. and Kessler, C., "Load Prediction of Hingeless Helicopter Rotors Including Drivetrain Dynamics," *CEAS Aeronautical Journal*, Vol. 12, No. 2, Apr. 2021, pp. 215–231. https://doi.org/10.1007/s13272-020-00483-6.

[17] Schwamborn, D., Gerhold, T., and Heinrich, R., "The DLR TAU-code: Recent Applications in Research and Industry," *ECCOMAS CFD 2006: Proceedings of the European Conference on Computational Fluid Dynamics*, Egmond aan Zee, Netherlands, Sep. 2006.

[18] Shaler, K., Branlard, E., and Platt, A., "OLAF User's Guide and Theory Manual," Tech. Rep. NREL/TP-5000-75959, National Renewable Energy Laboratory, Jun. 2020.

[19] van Garrel, A., "Development of a Wind Turbine Aerodynamics Simulation Module," Tech. Rep. ECN-C–03-079, Energy Research Center of the Netherlands, Aug. 2003.

[20] Gaertner, E. et al., "IEA Wind TCP Task 37: Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine," Mar. 2020. https://doi.org/10.2172/1603478.

[21] Hansen, M. O., Sørensen, N. N., Sørensen, J. N., and Michelsen, J. A., "Extraction of Lift, Drag and Angle of Attack from Computed 3-D Viscous Flow Around a Rotating Blade," *1997 European Wind Energy Conference*, Irish Wind Energy Association, Oct. 1998, pp. 499–502.