Harmonic balance acceleration of the Navier-Stokes Analysis of Wind Turbine Periodic Flows

Jernej Drofelnik*, M. Sergio Campobasso†

*PhD student, School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK, j.drofelnik.1@research.gla.ac.uk

†Senior Lecturer, Department of Engineering, Lancaster University, Lancaster LA1 4YW, m.s.campobasso@lancaster.ac.uk

Introduction

The aeromechanical design of wind turbines requires consideration of a large number of operating regimes. Most of these are unsteady, often periodic, and yield fatigue and power penalties. In the case of utility-scale horizontal axis wind turbines (HAWTs), periodic flow regimes include those due the blades rotating a) through wind stratifications of the atmospheric boundary layer, b) through the variable pressure field due to the presence of the tower, and c) in yawed wind (Fig. 1).

Navier-Stokes (NS) Computational Fluid Dynamics (CFD) has been shown to predict HAWT unsteady flows with accuracy suitable for reliable turbine design. The drawback of conventional NS CFD is its high computational cost. A time-resolved time-domain (TD) simulation of HAWT periodic flows requires long runtimes, as several rotor revolutions have to be simulated before the periodic state is achieved. Runtimes can be reduced by using the frequency-domain harmonic balance (HB) method for solving the unsteady NS equations [3,4]. The HB NS technology was implemented in the COSA NS CFD code. The poster presents the HB NS analysis of a 5 MW HAWT rotor in yawed wind and illustrates the vast potential of the HB NS technology for wind turbine design.

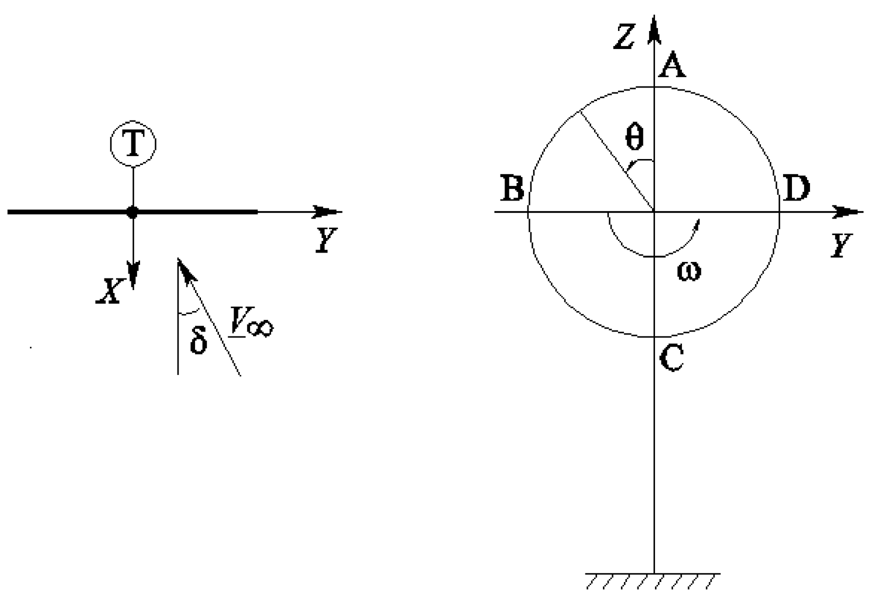

Figure 1. HAWT rotor in yawed wind.

COSA Navier-Stokes code

COSA is a finite volume structured multi-block NS CFD code for the analysis of fluid machinery for Renewable Energy applications, including HAWTs [3,4], vertical axis wind turbines [1,2], and oscillating wings for tidal power generation [5], The code presently uses the Shear Stress Transport turbulence model. General unsteady flow problems are solved with an implicit integration.

Nonlinear periodic flows are accurately and efficiently solved using the frequency-domain HB method. For given computational mesh (i.e. spatial resolution) and number of processors, this approach greatly reduces the runtime of periodic rotor flow analyses because: a) the method solves directly for the sought periodic flow field, bypassing the lengthy transient preceding the periodic regime, and b) using multi-frequency periodicity boundary conditions enables one to determine the periodic solution solving only the grid sector associated with one blade, thus reducing the computational cost proportionally to the number of rotor blades.

For 3D unsteady simulations, the use of high-performance computing is paramount: an extremely efficient and scalable distributed memory parallelisation of COSA has been developed in collaboration with EPCC, Edinburgh University. Fig. 2 presents a strong scalability test performed on ARCHER in summer 2015. The test case is the HB analysis of the flow past an oscillating 3D wing using a grid with 67 million cells. The scaling curve shows that the code can use 16,000+ cores without any loss due to parallel communication overheads.

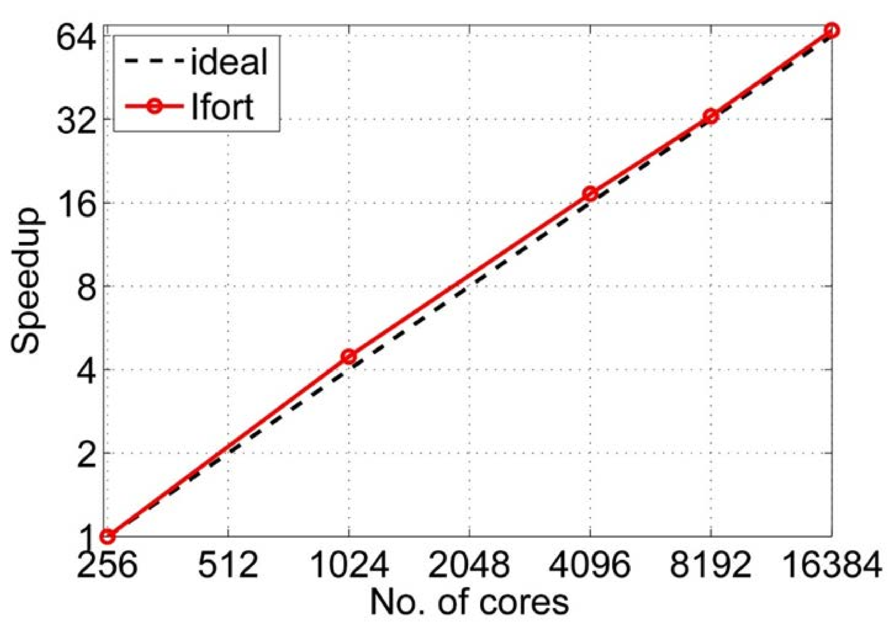

Figure 2. Strong parallel scalability test of COSA HB solver on ARCHER.

Verification and validation

The verification of all functionalities of COSA was carried out by a) solving flow problems for which analytical solutions exist and comparing such solutions to the computed ones, and b) computing with COSA and other established CFD codes the solution to complex unsteady flows and comparing the two sets of numerical solutions. A recent verification test consisted of comparing the TD simulations of an H-Darrieus rotor obtained with COSA and the commercial code FLUENT [1]. The grid used by the two codes, the COSA vorticity contours for close-to-optimum tip-speed-ratio, and the FLUENT vorticity contours for the same tip-speed-ratio are reported in the left, middle and right plots of Fig. 3, which highlight an excellent agreement of the two codes.

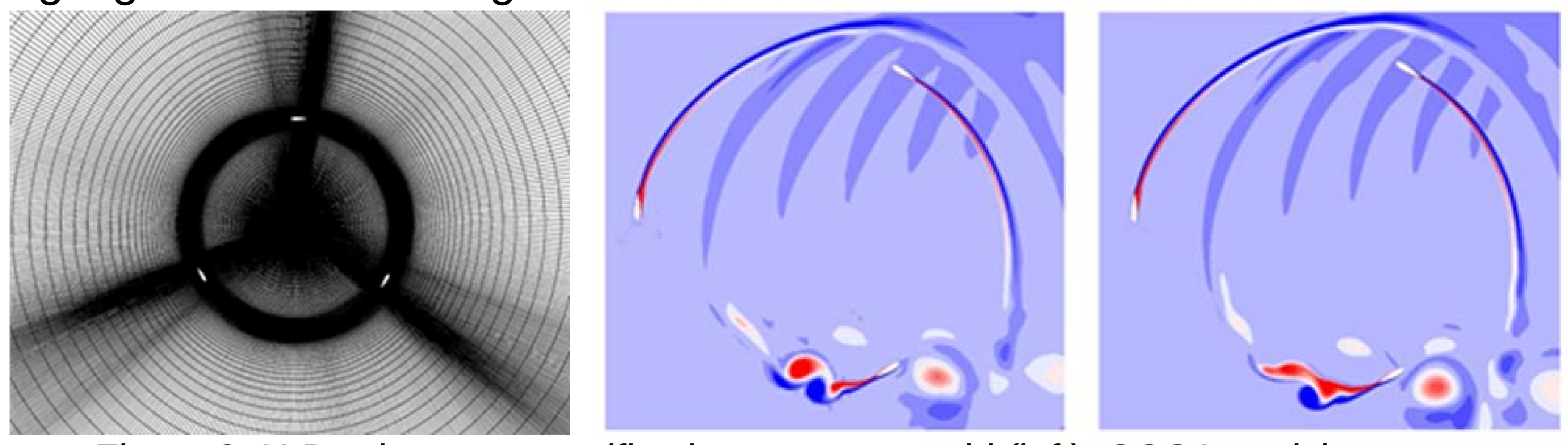

Figure 3. H-Darrieus rotor verification test case: grid (left), COSA vorticity contours (middle), and FLUENT vorticity contours (right).

One of the considered validation test cases was the flow field past the NREL Phase VI two-blade rotor.

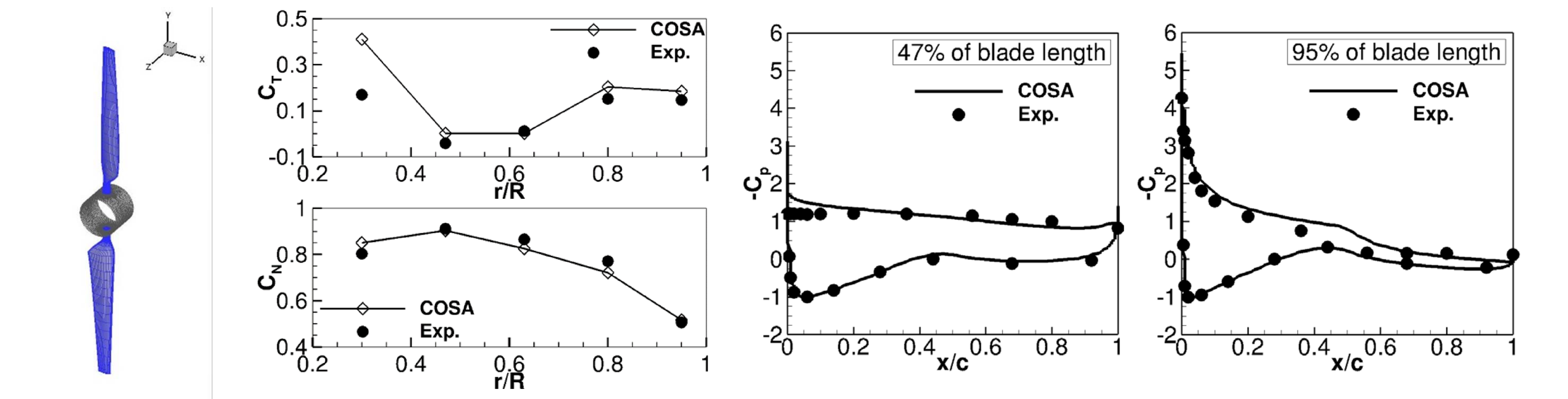

Figure 4. NREL Phase VI validation test case (13 m/s): geometry (left), blade torque and thrust coefficient (middle), blade static pressure coefficient (right).

Results

The demonstration of the HB NS technology for the rapid prediction is based on the simulation of the periodic flow of a 5 MW HAWT rotor (left plot of Fig. 5) subject to a 20˚ yaw error with a freestream velocity of 13 m/s. The blade sector grid used for the HB simulations has 3 million cells, whereas that of the complete rotor for the TD simulation is 3 times larger. A time-independent solution is obtained using at least 720 intervals per period. The middle and right plots of Fig. 5 compare thrust and torque coefficients of the TD 720 solution and the HB analyses using 1,2,3 and 4 harmonics. The TD 720 and HB 3 analyses present negligible differences.

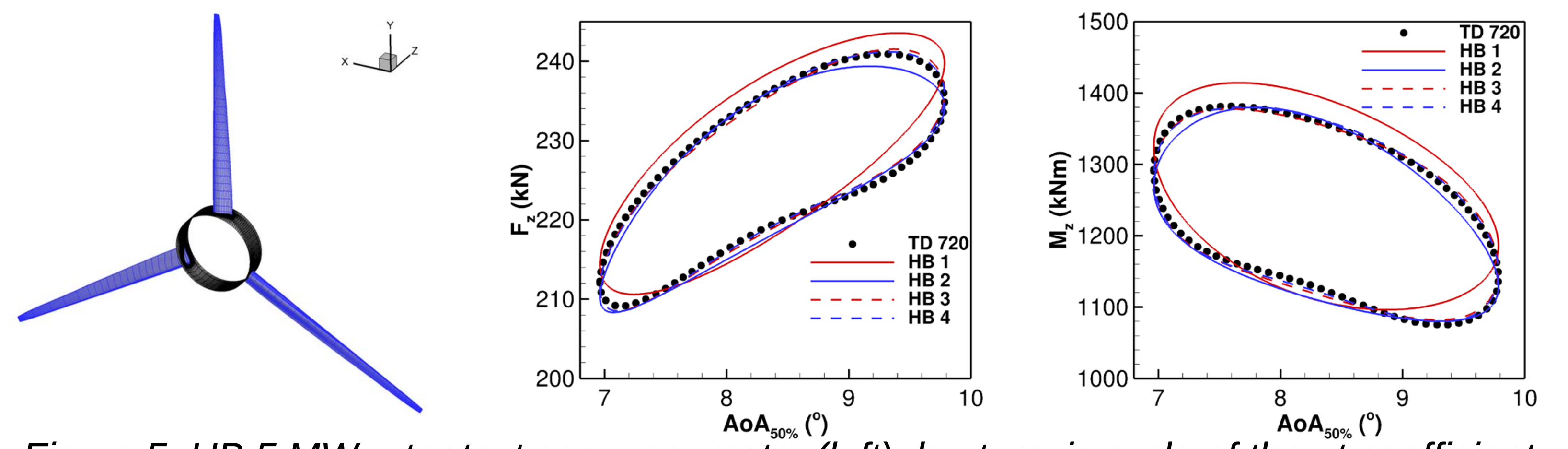

Figure 5. HB 5 MW rotor test case: geometry (left), hysteresis cycle of thrust coefficient (middle), hysteresis cycles of torque coefficient (right).

The ratios between runtimes of the HB and the TD 720 analyses are reported in the table at right, which shows that the HB 3 analysis accurately determined the sought periodic flow nearly 50 times faster.

	HB 1	HB 2	HB 3	HB 4
Speed-up	115.6	69.0	48.7	37.5

Rotor thrust and torque over one period predicted by the TD 720 and HB3 simulations are depicted in Fig. 6. Fluctuations are smaller than those on each blade, but shaft torque fluctuations yield electrical power flickering.

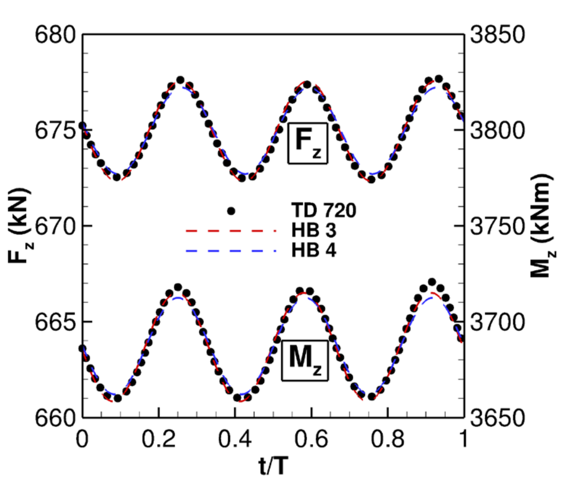

Figure 6: periodic variations of torque and thrust predicted by TD 720 and HB3 analyses.

Conclusions

- HB NS analysis resolves HAWT periodic flows with the same accuracy but much more rapidly than the conventional TD approach.
- Approach can be used to study turbine/wake interaction.

Bibliography

1) Balduzzi et al., *Three-dimensional CFD simulation of the time-dependent flow field generated by a one-blade H-Darrieus rotor*, High-Performance Computing-based Computational Fluid Dynamics for Offshore Renewable Energy (HPC-CORE) Workshop, April 2016, Lancaster.

2) Balduzzi et al., *Parametric and Comparative Assessment of Navier-Stokes CFD Technologies for Darrieus wind turbines Performance Analysis*, ASME paper GT2015-42663, 2015.

3) Campobasso, Drofelnik, *Harmonic balance acceleration of the Navier-Stokes Analysis of wind turbine periodic flows*, High-Performance Computing-based Computational Fluid Dynamics for Offshore Renewable Energy (HPC-CORE) Workshop, April 2016, Lancaster.

4) Campobasso, Gigante, Drofelnik, *Turbulent Unsteady Flow Analysis of Horizontal Axis Wind Turbine Airfoil Aerodynamics Based on the Harmonic Balance Reynolds-Averaged Navier-Stokes Equations*, ASME paper GT2014-25559.

5) Drofelnik, Campobasso, *Comparative Turbulent Three-Dimensional Navier-Stokes Hydrodynamic Analysis and Performance Assessment of Oscillating Wings for Renewable Energy Applications*, International Journal of Marine Energy, May 2016.