Oral presentation | Fluid-structure interaction
Fluid-structure interaction-II
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[2-A-03] Exploring Static Rotor Approach and Dynamic Rotor Simulation for Magnus Effect VAWT using Direct Forcing Immersed Boundary (DFIB) Method

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Exploring Static Rotor Approach and Dynamic Rotor Simulation for Magnus Effect VAWT using Direct Forcing Immersed Boundary Method.

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1 Introduction

Wind turbines are widely implemented as a global renewable energy technology. Currently, two main types dominate the landscape: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). Compared to HAWTs, VAWTs emerge as particularly appealing and well-suited options for areas with less predictable wind speeds. One type of VAWT that has recently gained prominence due to its unique ability to generate electricity even in strong winds is the Magnus vertical axis wind turbine (VAWT). Magnus VAWT was patented in 2017 by Atsushi Shimizu, a Japanese engineer who is also the founder of the Challenergy company [1]. This wind turbine utilizes the Magnus effect in conjunction with a vertical axis orientation. The mechanism relies on the lift and drag produced by rotating cylinders to propel the rotor and generate power.

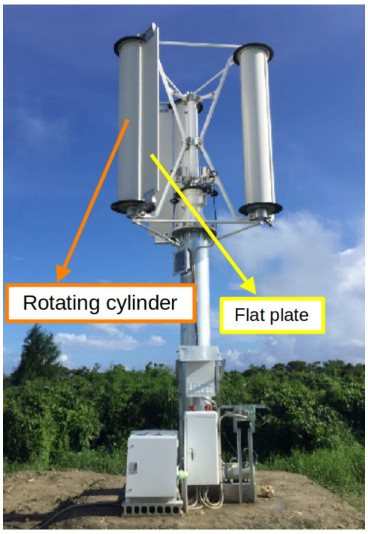

Figure 1: Challenergy, Inc.'s Magnus effect VAWT, with blades' consisting of a rotating cylinder and a flat plate.

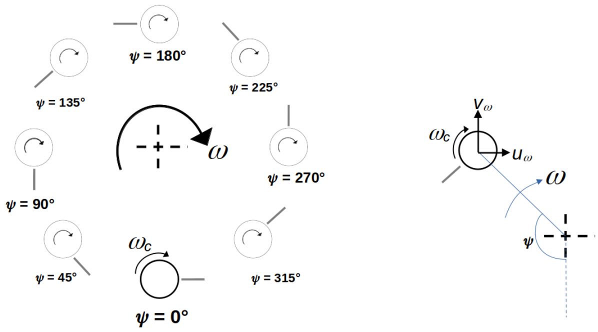

Figure 2: Eight positions used in static rotor simulation (Left). Solid velocity is applied to represent the effect of rotor's angular velocity (ω) (Right).

In this study, the blade design was adopted from the existing design by the Challenergy, Inc. A flow enhancement, represented by a flat plate was placed in such a way that a certain gap to the cylinder as in Fig. 1, without being dependent on cylinder rotation. The plate moves to follow the movement of the cylinder as it revolves around the rotor axis. The position of the flat plate is expected to change the flow pattern and the Magnus force, resulting in a unidirectional torque at each position of the blade while maintaining a constant cylinder rotation speed to minimize the energy input.

The direct forcing immersed boundary (DFIB) method allows for the use of Cartesian grids, providing flexibility in handling various fluid-structure interaction (FSI) scenarios where structures may undergo significant deformations or displacements. Utilizing such numerical methods offers an economical and efficient way to explore various geometries and operating conditions, aiding in potential turbine performance improvements. However, fine grid resolutions are necessary to accurately capture the fluid behavior near immersed boundaries, leading to increased computational costs.

Besides employing a dynamic rotor simulation to resolve the flow, which requires a large number of mesh, there is another approach called the static rotor approach [2, 3]. This method simplifies the simulation by treating the rotating parts as if they are stationary, allowing for a reduced number of mesh and potentially significantly reducing computational costs. In an effort to deepen the literature information and address some research gaps, the present study has the main objective of exploring the utilization of the static rotor approach for predicting the Magnus effect VAWT torque coefficient (C_T) and the flow behavior.

2 Research Methodology

The static rotor approach employs eight rotor positions, separated at every 45° as depicted in Fig. 2, to represent the evolution of C_T in a single rotor cycle. The tangential velocity resulting from the rotor's rotation at a constant tip speed ratio (TSR) was applied to the blade. TSR is defined as $\omega\, R/U_\infty$, where ω and R represent the rotor's angular velocity and radius, respectively. This approach ensures that the rotor remains stationary during the simulation, while still imparting rotation and the associated momentum terms to the flow.

The non-dimensional momentum conservation equations including a virtual force term defined by the DFIB method are discretized on a Cartesian mesh by means of finite volume techniques. They are then solved using an in-house solver, called TIGER-F, developed in the Fortran programming language. A large eddy simulation (LES) with the Smagorinsky-Lilly model is used to capture the effects of unresolved small-scale turbulent fluid motions.

Static rotor simulations were executed on the TAIWANIA 3 supercomputer at the National Center for High-performance Computing (NCHC) in Taiwan. Each computation node is equipped with 2 Intel® Xeon® Platinum 8280 2.4GHz CPUs (56 cores/node). Message Passing Interface (MPI) and Open Multi-Processing (OpenMP) techniques are employed to parallelize the computational workload across multiple nodes and distribute the computational load to each core. For each position of the static rotor simulation, 224 CPU cores (4 nodes) were utilized to process a mesh of around 20 million elements.

Multi-GPU computation was employed for dynamic rotor simulations on the TAIWANIA 2 GPU cluster, with each computation node equipped with 8 NVIDIA® Tesla V100 GPUs. For each dynamic rotor simulation, 8 GPUs were utilized, handling approximately 120 million mesh elements.

3 Results and Discussion

Simulations were conducted in the sub-critical flow regime with $Re = 5000$, a constant TSR of 0.8, and the cylinder's spin ratio $\alpha = r_c\, \omega_c/U_\infty = 3$. Two cases of different blade configurations were used: C1 and C2, as shown in Fig. 3. C1 represents the optimized blade configuration, and C2 is one of the design points employed in the previous parametric study [4].

Figure 3: An illustration of blade configurations.

It can be seen in Fig. 4 that there is a difference in the C_T profiles of the two blade configurations, C1 and C2, particularly in the interval $225° < \psi < 360°$. In this interval, it is apparent that the C1 blade configuration is able to suppress the opposing torque better than C2, resulting in a generally higher net torque in a single rotation. Static and dynamic rotor simulations resemble similar trends in C_T profiles. However, the differences in the values generated by each method are considerable.

Significant flow pattern differences are especially noticeable when the blade is on the leeward side ($225° < \psi < 360°$), as depicted in Fig. 5. A static rotor approach lacks the ability to capture dynamic effects caused by rotor movement, as it provides only instantaneous velocity without considering structural displacement.

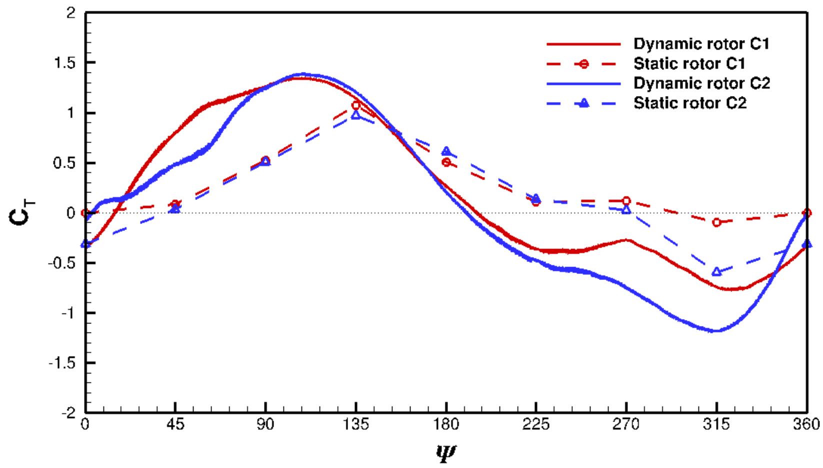

Figure 4: C_T profiles in one rotor cycle.

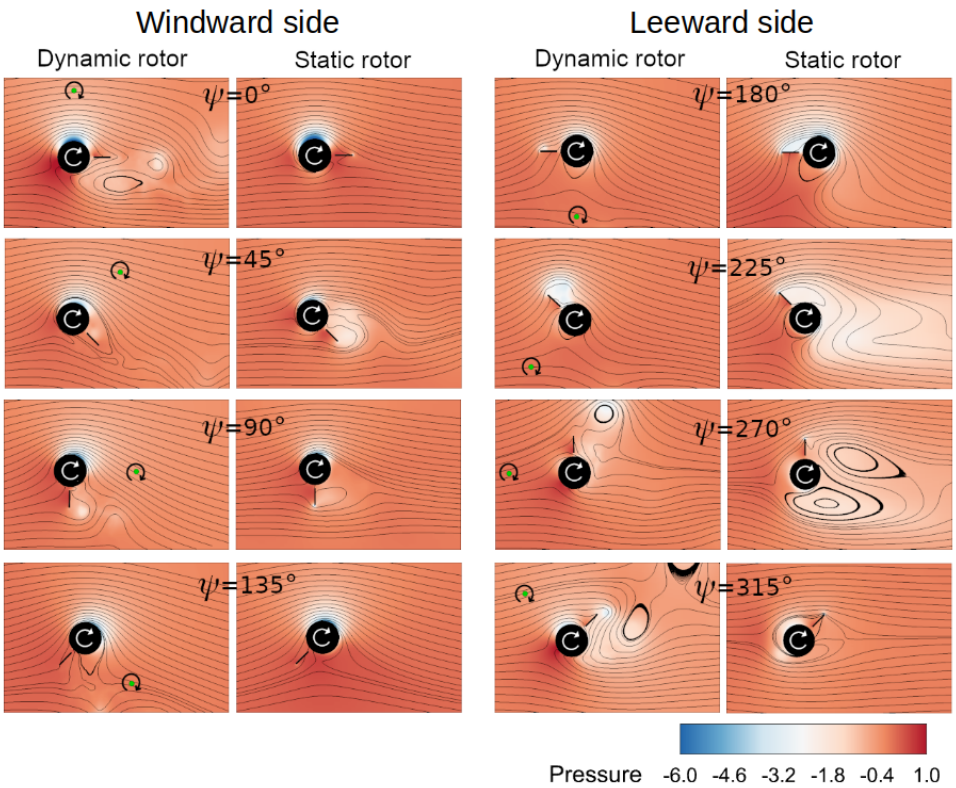

Figure 5: Pressure contours and streamlines of C1 at various ψ. The rotor's center of rotation is marked as a green point.

The findings suggest that although static rotor simulations require less computational resources compared to dynamic simulations, they are adequate for conceptual analysis or design optimization of Magnus effect VAWTs. However, this approach is limited in its ability to provide detailed insights into flow-structure interactions and accurate performance predictions.

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