General Exam Research Abstract

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Unsteady airfoil aerodynamics with applications to vertical axis wind turbines

Introduction: One of the challenges in the implementation of vertical axis wind turbines (VAWTs) is the difficulty in accurately predicting their performance. Recently developed double-multiple streamtube (DMST) models attempt to do this by calculating the aerodynamic forces experienced by the individual blades throughout a rotation, and equating them to the momentum loss of the flow through the turbine. The aerodynamic force is calculated using airfoil lift and drag coefficients found in literature. However, these coefficients are based on steady conditions, whereas the blades of VAWTs experience periodically varying loads. This is because lift and drag exhibit a high Reynolds number dependency, and full-sized VAWTs operate at Reynolds numbers of order 10^6. Most research facilities do not have the experimental setup necessary to study unsteady flows with Reynolds numbers in this range.
However, existing research shows that dynamic stall causes the lift on an airfoil under unsteady conditions to differ drastically from that under steady conditions. The objective of my research is therefore to characterize the unsteady aerodynamic flows governing airfoils at high Reynolds numbers. Specifically, the drag and lift forces, as well as the wakes of pitching airfoils will be examined. The resulting data can be used by DMST models to predict VAWT performance.

Research Plan: Scaled down models of pitching airfoils will be studied to assess the effects of dynamic stall on wake formation, and lift and drag forces. This study will be conducted in the High Reynolds number Test Facility (HRTF) at Forrestal Campus (Figure 1). The HRTF is a recirculating-type low velocity, high static pressure tunnel that uses compressed air as a working fluid. It achieves dynamic similarity by matching non-dimensional parameters to full scale conditions[1]. For airfoils the relevant parameters are the Reynolds number, the Mach number and the Strouhal number (reduced frequency).

By increasing the tunnel pressure, high Reynolds numbers can be achieved while keeping the Mach number low, and the Strouhal number high. This is necessary because an increase in Mach number would lead to compressibility effects, and both the Reynolds number and the Strouhal number of the experiment must match the full-scale condition for the results to be directly relevant to real VAWT blades. The Strouhal number

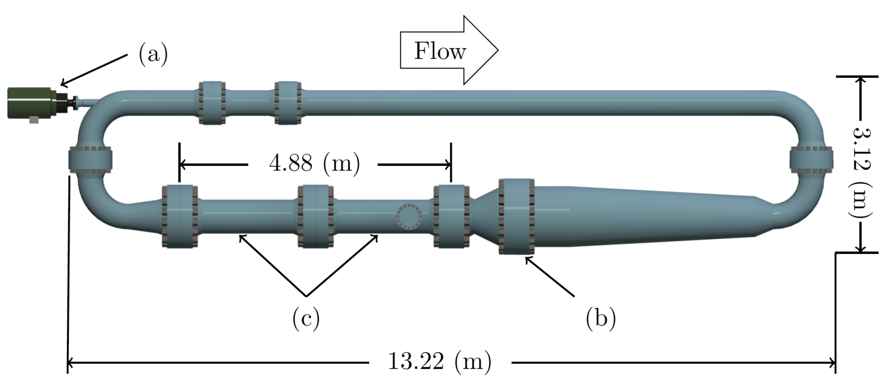

Figure 1: HRTF consisting of an external motor (a) driving an internal impeller pump, which moves air to the conditioning and contraction section (b), from where it moves to the test section (c).

could also be matched by an increase in the pitching frequency. However, this is difficult to implement experimentally. The HRTF can support static pressures up to 230 bar which enables Reynolds numbers and Strouhal numbers to match real-world conditions. For this study, Reynolds numbers of order 10^6, and Mach numbers below 0.1 will be used. First, symmetric airfoils will be examined. Based on the success of these initial experiments the study will be extended to include cambered airfoils.

Pitching an airfoil can lead to the formation of vortices at the leading edge that significantly affect the instantaneous pressure distribution around the airfoil and therefore the forces experienced under non-equilibrium conditions. Aerodynamic stall is the phenomenon where the viscous boundary layer separates from the surface of an airfoil, significantly reducing the lift force (Figure 2). This occurs when the airfoil's angle of attack is too large, so that the pressure gradient in the boundary layer is too high for the flow to stay attached[2].

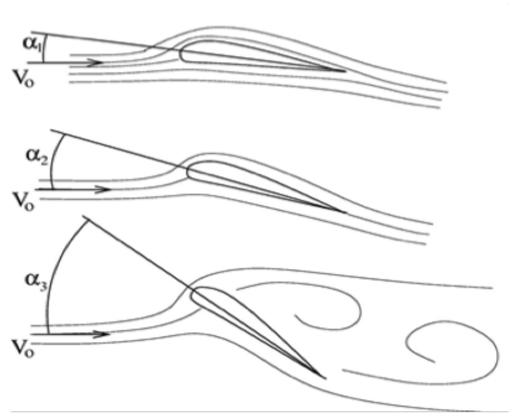

Figure 2: Airfoil at varying angles of attack. At α_3 stall occurs.

In aircraft flight, stall generally needs to be avoided in order to maintain sufficient lift force, but if the angle of attack is increased rapidly and temporarily before the flow reaches equilibrium, the lift force momentarily increases due to the formation of a very low-pressure vortex at the airfoil's leading edge. This vortex convects along the top surface of the airfoil until it reaches the trailing edge and the lift force drops significantly. Insects and birds use this phenomenon to fly, but it also occurs at the rotating airfoils of helicopters and wind turbines, and at aircraft wings during maneuvers or fluctuating wind conditions. Therefore, steady approximations are inaccurate in these conditions, and exact and transferable data on the drag and lift forces created during dynamic stall are necessary to create models that accurately predict VAWT performance.

I will begin by characterizing the lift and drag forces acting on pitching airfoils in order to understand the dynamic loads they experience. Then, I will investigate their wakes, in particular their vortex shedding. In order to conduct the proposed experiments, I will begin with a preliminary study of a static airfoil that is exposed to a periodically varying mean flow velocity in the HRTF. This simplified setup will provide preliminary data under unsteady conditions, which will be used to validate the experimental setup. I will then design an airfoil model for the HRTF that can rapidly tilt around its center of mass in order to create periodic pitching. All airfoils will be equipped with force sensors to record the lift and drag forces. Existing equipment will be used to characterize the wakes of the airfoils. The data can be used in models that predict the performance of wind turbines, subsonic aircraft or submarines.

1. Miller, Mark A., Subrahmanyam Duvvuri, Ian Brownstein, Marcus Lee, John O. Dabiri, Marcus Hultmark. "Vertical Axis Wind Turbine Experiments at Full Dynamic Similarity." *Journal of Fluid Mechanics* (2018): 707-720.
2. Corke, Thomas C., and Flint O. Thomas. "Dynamic stall in pitching airfoils: aerodynamic damping and compressibility effects." *Annual Review of Fluid Mechanics 47* (2015): 479-505.