Assignment #6: Propeller Aerodynamics — ME 515

due 4/15/2020 before midnight via Learning Suite — 50 possible points

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The objective of this homework is to implement a basic blade element momentum model and validate its performance against experimental data for the APC thin electric 10 x 5. This journal article: Blade Element Momentum Modeling of Low-Reynolds Electric Propulsion Systems provides some helpful background.

6.1 *Airfoil corrections.* The accuracy of blade element theory depends heavily on using reliable airfoil section data. Providing good data is more difficult than it initially sounds. In general, the airfoil type/thickness, angle of attack, Reynolds number, and Mach number all change along the blade length. Additionally, rotating blades generate spanwise flow altering performance compared to 2D flow, and so other parameters like the advance ratio and solidity indirectly affect the lift and drag coefficients. For the purposes of this homework we will simplify things considerably.

First, our blade only uses one airfoil and it is of constant thickness ratio along the blade: NACA 4412 (actually there is a different airfoil along the first 5% of span, but ignoring the hub region will have minimal impact). Second, we will restrict our attention to comparing against data that is relatively constant in Reynolds number: $\text{Re} = 1.5 \times 10^6$ (warning: this is Reynolds number based on rotor diameter, as is used in the journal paper, not Reynolds number based on chord). Third, rather than analyze across various Mach numbers we will use the Prandtl-Glauert correction (or Karman-Tsien).

Unfortunately, reducing the angle of attack range will not produce acceptable results. As compared to wings, propellers must operate across a broader range of inflow conditions and parts of the blade will be stalled. To more accurately predict performance the range of angle of attacks must extend well past stall in both directions. A panel code like XFOIL cannot provide sufficiently accurate data across this full range as the integral boundary layer methods assumed attached flow. There are a few options for how you can do this:

- The paper above cites other studies containing post-stall experimental data for this particular airfoil. You can use that data directly. Unfortunately, such data is not available for most airfoils in general, hence the other methods below.
- Use a panel code (either the one you developed or XFOIL) for a range of angles of attack just past stall. Then apply an extrapolation method to extend the data to high angles of attack. One simple method is the Viterna method. Wind turbines must extend airfoil data all the way from $-180°$ to $180°$ because the wind could come from any direction, but for a propeller analysis extending to ± 30– degrees or so should be sufficient.
- Perform a viscous CFD analysis across the range of angles of attack.

One final consideration is rotational corrections. The paper provides one simple method, though many others exist. Sometimes these are computed on the fly as in this paper, and other times they are precomputed and built into the look up tables (which is sometimes helpful during optimization to ensure that the inputs are always reliable).

In the end, you need one function that provides the lift and drag coefficient as a function of angle of attack. You can use linear interpolation like the paper does, or splines. The latter is preferable for design optimization because it gives you continuous first derivatives, though not necessary for this homework. Plot the lift and drag coefficients across your range of angles of attack.

6.2 *Blade element momentum theory.* Implement the blade element momentum method and compare your results to the experimental data. You can extract data from the paper, or use this tabulated data from UIUC. These two independent sets of experiments compare well as shown in the paper, so either should be fine for comparison. The UIUC site also tabulates the chord/twist distributions. Compare your thrust coefficient, power coefficient, and efficiency as a function of advance ratio.