DFDC Blade Blockage Model

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Blade blockage effects arise in ducted fan systems due to physical blade volumes displacing fluid volumes within the confined duct, leading to increased velocities through the disk(s). Analogous to a venturi, the flow accelerates at the disk according to the relative reduction in fluid cross-sectional area. If we assume this velocity increase to be axial only (tangential velocities being unaffected), the blade sees higher velocities at a reduced angle of attack. Consequently, since DFDC v0.70 does not model this effect, the code overpredicts torque vs. rpm. While the discrepancies are small for low to moderate solidity cases (typically 3 or 4 percent) and can readily be accounted for, they become more problematic for highly loaded, high solidity cases where blade volumes represent a significant proportion of fluid volumes, resulting in off-optimum designs and anomalous predictions of power and efficiency. This represents the one significant omission in DFDC's formulation, limiting the code's effectiveness for high solidity fans.

Figure 1 illustrates the intersection of a rotor and an axial plane (disk). The colored area represents the intersection, while 'solid' and 'fluid' refer to arc lengths at radius r. It follows that at a particular radius and axial coordinate, assuming incompressible flow, axial velocities are augmented over nominal by a factor of (*solid* + *fluid*) / *fluid*. This can of course be extended to any blade number. It follows that, at each blade radius (rotor point), the velocity factor will vary continuously over the axial extent of the blade, from unity at the leading edge to some maximum value at max airfoil thickness, then back to unity at the trailing edge. It follows that a fully analytic solution at each rotor point would require the precise definition of blade geometry in three dimensions, followed by analysis of the relevant airfoil in a continuously changing flow field over its chord length – not impossible but complex and computationally intensive. A more pragmatic approach is required.

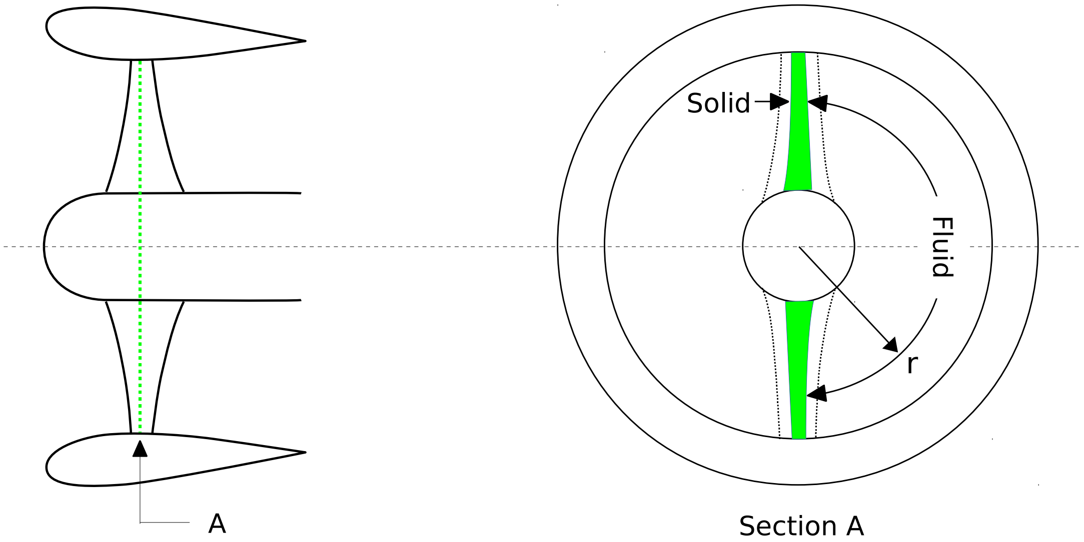

Figure 1

Fortuitously, the preliminary step in any realistic blade blockage correction – definition of blade geometry in three dimensions – becomes a simple matter with the ESLOFT lofting extension. ESLOFT provides blade section area data at each loft station which can readily be applied to calculate an *average* velocity factor (averaged over the axial extent of the blade) at each rotor point. Figure 2 illustrates the basic idea. One imagines a cylindrical surface containing the blade sections at a particular radius, with total area given by:

Cylinder_area = 2 * Pi * r * Chord * Sin(Beta)

Total blade section area is calculated from normalized section area data provided by ESLOFT:

Total_section_area = Unit_section_area * Chord * Chord * Blade_number

The average velocity factor at the relevant radius is then given by:

Velocity_factor = Cylinder_area / (Cylinder_area – Total_section_area)

Physically, this approximation can be interpreted by idealizing the blade profile as a rectangle of equivalent area, as depicted in Figure 2. However, those regions of the airfoil contributing most to aerodynamic lift (and hence to blade forces) are also the regions of greatest thickness, which see a local velocity factor significantly higher than our calculated average, thus compounding the effect.

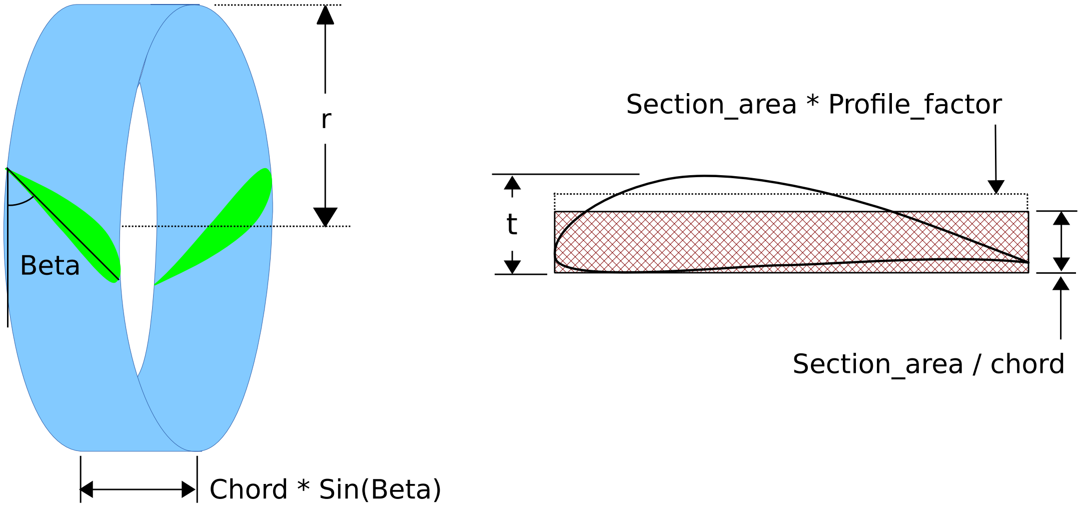

Figure 2

Since airfoil sections typically have a maximum thickness of 1.4 to 1.5 times their average thickness, the velocity factor at max thickness will be up to 1.5 times the calculated average. We can therefore surmise with some confidence that the *effective* section area (as applicable to the above formula) will be within the range 1.1 to 1.4 times the average. To implement this calibration we introduce a ‘profile factor’ which simply scales section area to account for these considerations. Hence:

Effective_section_area = Total_section_area * Profile_factor

The above reasoning determines the profile factor to within about 12 percent around a mean of 1.25. (Note that this uncertainty applies to the magnitude of the correction itself – the corresponding variation in DFDC output will be at least an order of magnitude less.) The profile factor can be adjusted by the user to calibrate the model against empirical data and will be more precisely determined as test data becomes available. (To this end, users having test data from DFDC designs are invited to contact the author.)

When blade blockage correction is active, the velocity factors are applied at two places in the DFDC code where blade relative velocities are calculated (in subroutines WCALC and SETROTVEL), by applying the factors to axial velocities seen by the blade at each rotor point. While the resulting output appears to be consistent both internally and with test data, inserting the velocity factors optimally into the solver is somewhat subtle and, as of this writing, remains experimental.

Program Execution

The following commands are appended to the OPER menu (v3.2a and later):

```
BB       Toggle Blade Blockage correction
BBLS     List current blade blockage data
BBUP     Update blade blockage data
BBPF     Change blade blockage Profile Factor
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Blade blockage correction becomes available only when each disk has been lofted in LOFT. Blade blockage data is stored automatically whenever one leaves a disk in LOFT. The code performs the above calculations at each loft station then splines the data to the rotor points, the stored data representing the axial velocity factor (including the current profile factor) at each rotor point. Note that this data is derived from geometry alone and is automatically regenerated whenever blade geometry is modified, as follows:

- When designing a new blade with DESI.
- When editing blade geometry with MODI.
- When adjusting blade pitch with PITC.

Note that lofts need be set up only once, defining a particular t or t/c distribution and airfoil set for each disk. Lofts and blade blockage data will then update automatically with each change in blade geometry.

Design with blade blockage generally requires three or four ACT/DESI iterations to converge on design CL and BGam. It can be instructive to design a blade with and without blade blockage and compare the designs. PVEL provides insight into the mechanism of the effect.

Converging a case with THRU and variable pitch may require a few iterations while manually updating blade blockage data with BBUP. The profile factor can be changed at any time with BBPF followed by updating the current data with BBUP.

Performance

The correction is robust and adds nothing to calculation times. The matter of interest is whether this simple blade blockage model can account for discrepancies seen in DFDC test data and provide the means to design more highly optimized ducted fans. To date the results are encouraging, with trends seen in testing being consistently predicted by the code. While quantitative predictions appear to be in the ballpark, further validation and calibration requires test data beyond that currently available to this author.

Crucially, the correction is *explicit* (the one ‘free’ parameter we hope can be pinned down against test data) and it is *universal* (in principle it is equally applicable to any DFDC case, given appropriate lofts). Moreover, the correction reveals that blade blockage is a more powerful effect than commonly recognized, due to the fact that the two primary consequences – higher blade relative velocities at a reduced angle of attack – tend to mask each other on the test stand. A test might demonstrate slightly higher rpm than predicted without revealing that both CL and BGam are highly skewed and off-optimum. For high solidity cases, in particular, the model reveals that uncorrected designs have too much chord and not enough beta (especially towards the hub), to such a degree that serious anomalies can arise. While it is too soon to tell how generally applicable and effective this model will be in predicting blade blockage effects, all indications are that predictions with the correction will prove closer to the real world than predictions without it.

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