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Application of Engineering Models to Predict Wake Deflection due to a Tilted Wind Turbine

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Abstract

It is a known fact that the power produced by wind turbines operating inside an array decreases due to the wake effects of the upstream turbines. It has been proposed previously to use the yaw mechanism as a potential means to steer the upstream wake away from downstream turbines, however such a mechanism introduces control complications due to changing wind directions. Deflecting the wake in the vertical direction using tilt, on the other hand, overcomes this challenge. In this paper, the feasibility of steering wake is explored in a simple uniform inflow case. This is done by trying to model the wake deflection as a function of the yaw/tilt angle and the rotor thrust, initially using the momentum and vortex theories. Thereafter, a relatively more promising empirical model based on a set of actuator disc CFD computations is proposed. Finally, comments are made on the feasibility of wake control using yaw/tilt.

Objectives

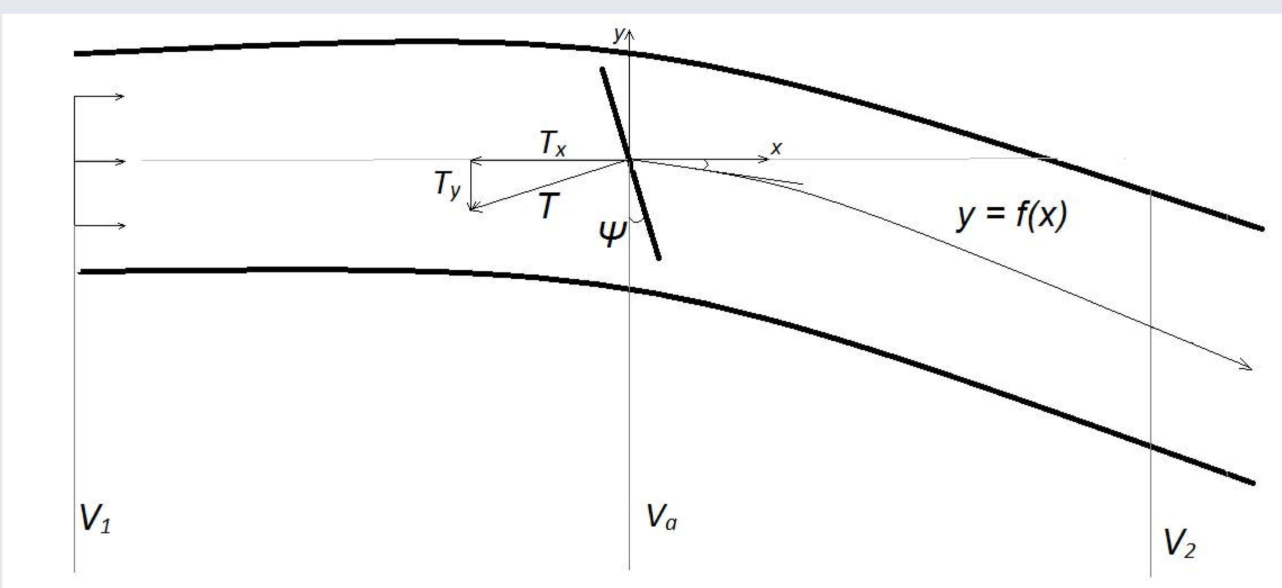

Figure 1: Schematic of the simplified problem

The objective of the current study is to estimate the wake path as a function of the disc loading and the tilt angle, and thereby assess the feasibility of using yaw/tilt as a means to steer the wake away from downstream turbines. This is done using:

1. BEM and vortex based models to derive an analytical expression, and
2. Empirical relations established using data from actuator disc CFD computations.

Analytical Approach

1. Assumptions:
   a) The change in the momenta in the y and the x directions are proportional to the rotor thrust force components in the respective directions:

$$\tan\psi = \frac{a_y}{a_x}$$

   b) This relation is true for all *x*:

$$\tan\psi = \frac{a_y}{a_x} = \frac{a_y(x)}{a_x(x)}$$

2. Consider a rotor operating in axial flow, has one blade with infinite TSR, and is lightly loaded. The axial induction along the centerline can be calculated as a function of downstream distance by a simple vortex model assumption [6], as:

$$a_x(x) = \frac{(1-\sqrt{1-C_T})}{2}\left(1+\frac{x}{\sqrt{R^2+x^2}}\right),$$ and $$a_y = a_x \tan\psi$$

Observations

1. The analytical model does NOT compare well with the CFD data, and therefore assumption **(b.)** is probably invalid. Figure shown is an example case of $C_T = 0.64$, $\psi = 30^0$.
2. There exists a self similarity in the wake path function. Figure (2) shows all data from C_T = {0.36, 0.64, 0.80, 0.89}, and ψ = {50, 100, 200, 300}. When this data is normalized as,

$$\tilde{y}(x) = \frac{y}{C_T \tan\psi} = 0.24x$$

interestingly results in a self similarity as shown in figure (3). From this, a new relation between *y, x,* C_T and ψ can be written as:

$$y(x,C_T,\psi) = 0.24 x C_T \tan\psi$$

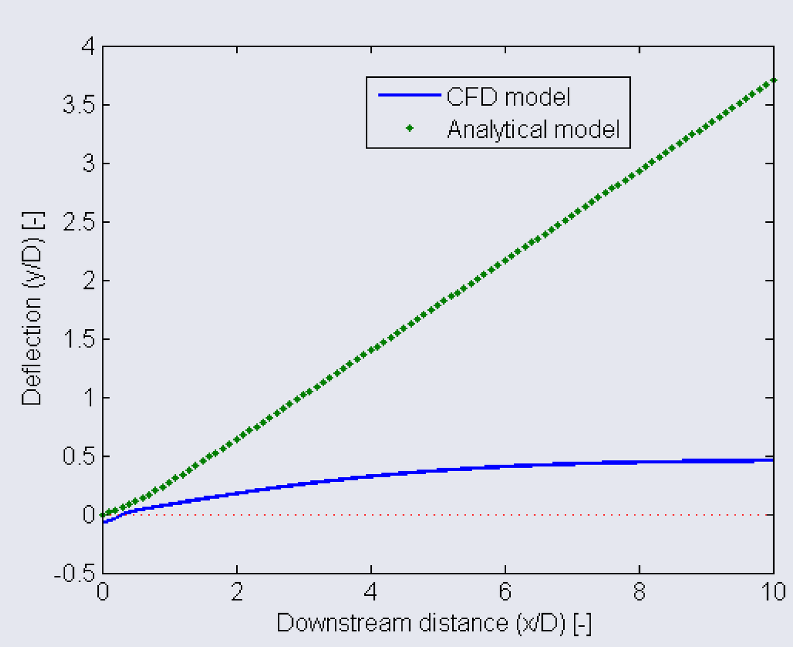

Figure 2: Comparison between the analytical model and CFD data for a test case of $C_T = 0.64$, $\psi = 30^0$.

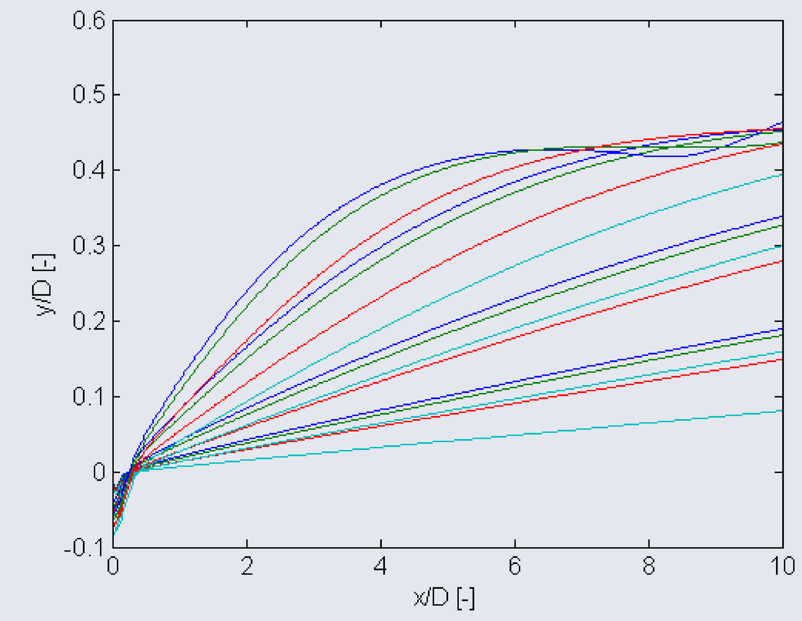

Figure 3: Wake path function plotted for all values of C_T and ψ.

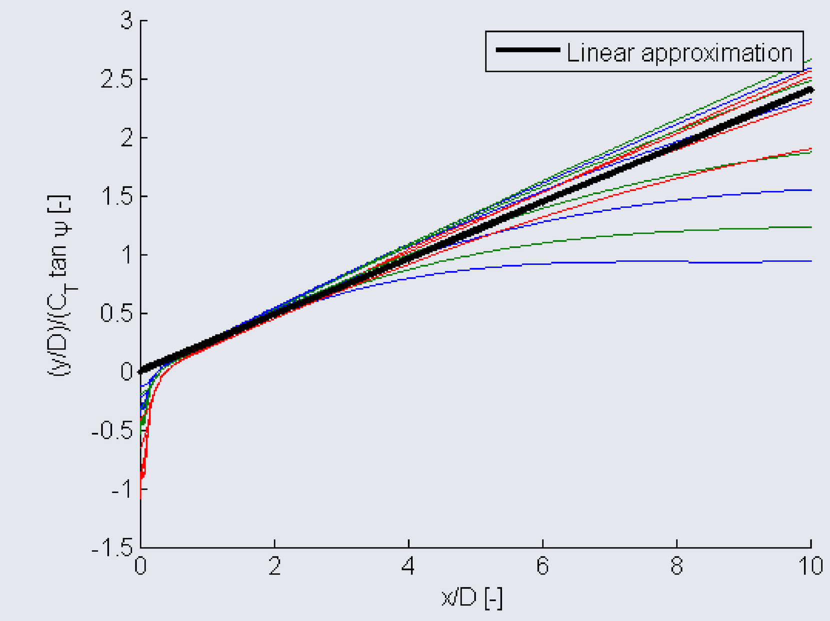

Figure 4: Normalized wake path function.

Results

Figures (5), (6) and (7) show a comparison between the empirical model and the corresponding CFD data in different cases. The model works reasonably well for low tilt angles. As the tilt angle is increased, the deviation between the model and the CFD data starts to grow, for example see figure (8). In any case, the deflection of the wake obtained using even the highest of the ψ and C_T values is only menial, and therefore wake control using tilt (or yaw) seems impractical.

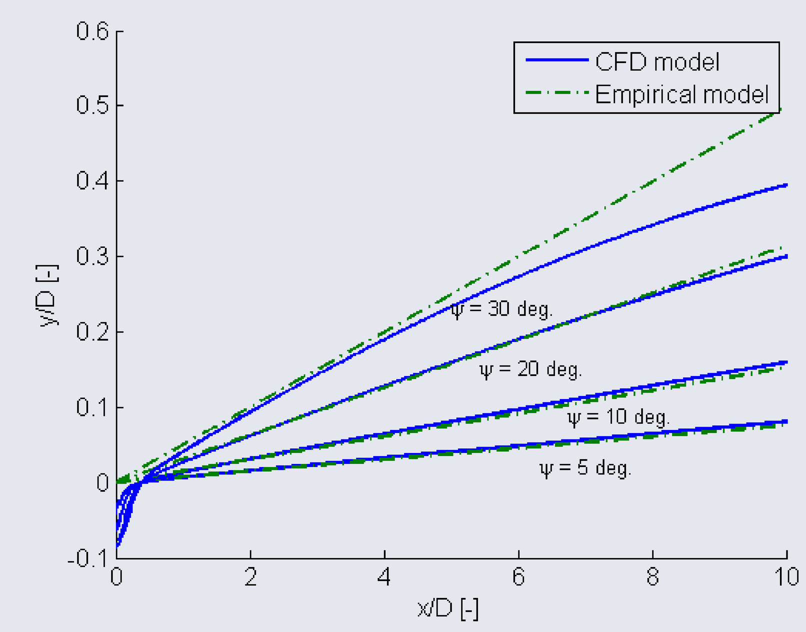

Figure 5: $C_T = 0.36$.

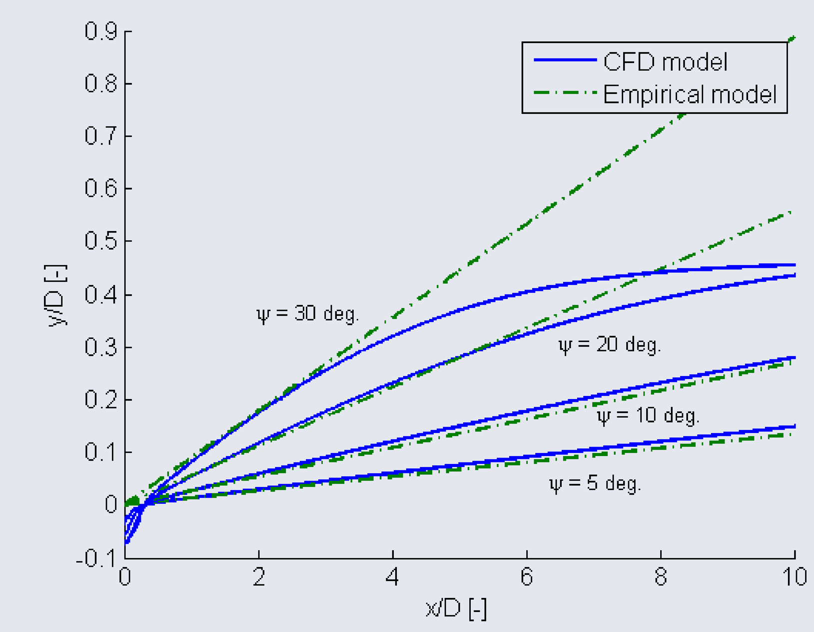

Figure 6: $C_T = 0.64$.

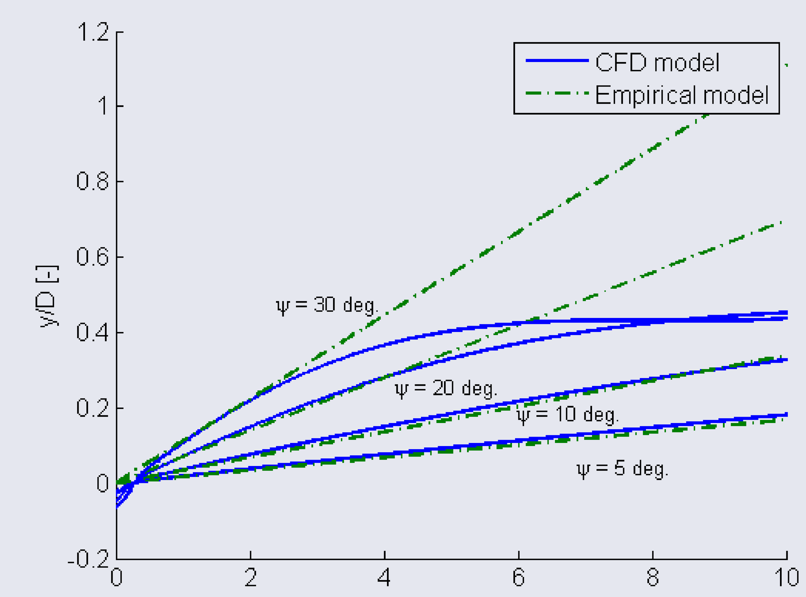

Figure 7: $C_T = 0.80$.

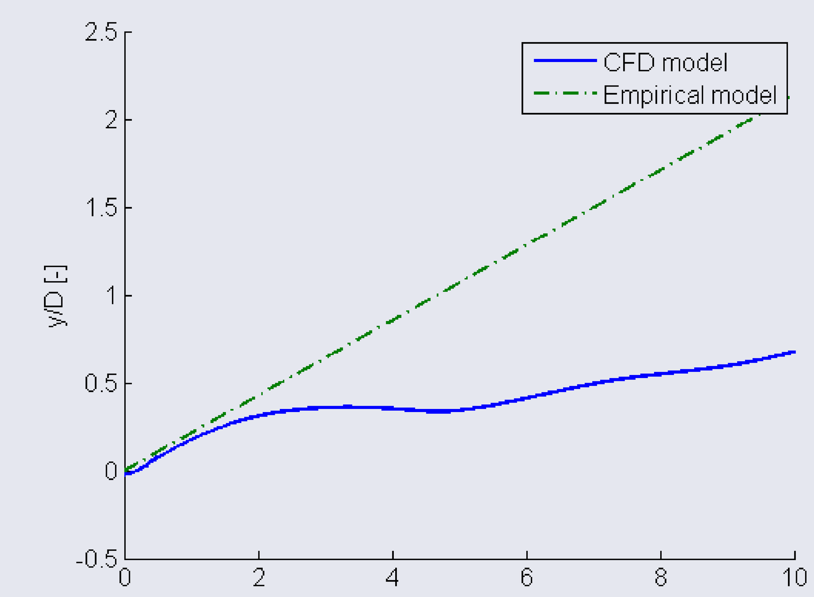

Figure 8: $C_T = 0.89$, $\psi = 45^0$.

Conclusions

- The empirical model is believed to give a reasonable estimate for the wake path function for small tilt angles.
- In theory, it is possible to steer the wake away from a downstream turbine, however the amount of tilt and the distance between the turbines required to accomplish this seem to suggest that this concept is rather impractical.
- Meandering and turbulence effects may dominate at larger downstream distances, which makes the control of the turbine based solely on the current concept a challenge.

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