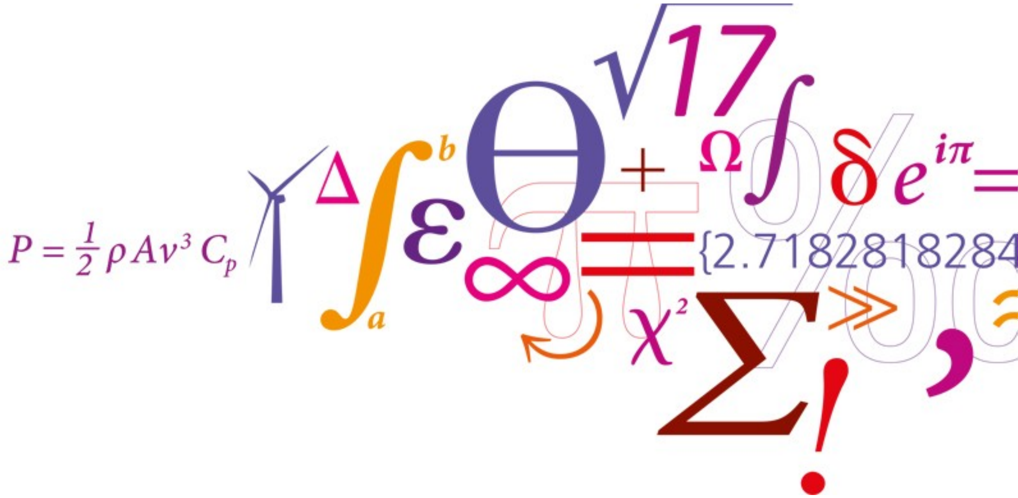
A New Tip Correction Based on the Decambering Approach

Jens N. Sørensen
Kaya O. Dag
Néstor Ramos-García

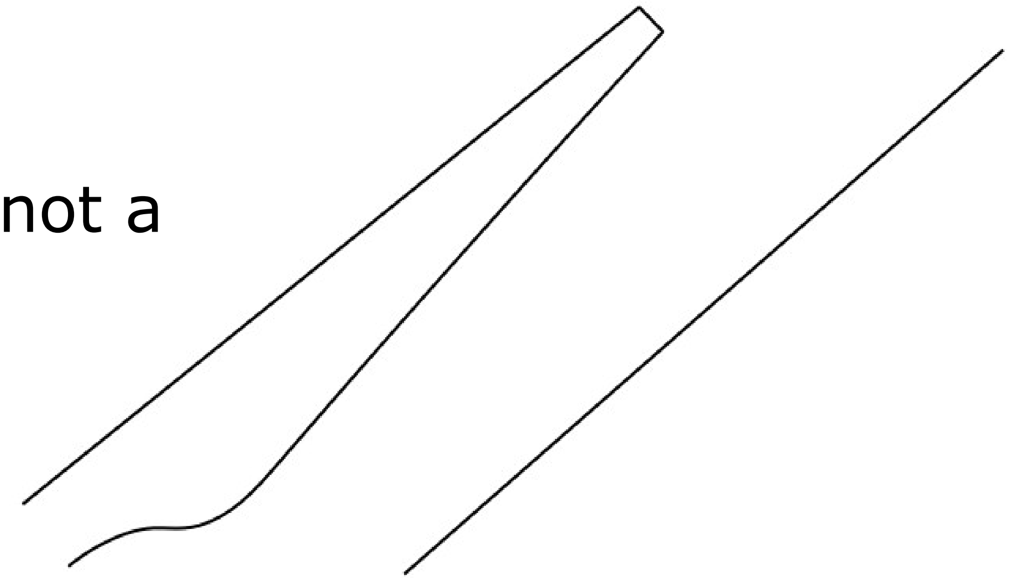


DTU Wind Energy
Department of Wind Energy

Overview

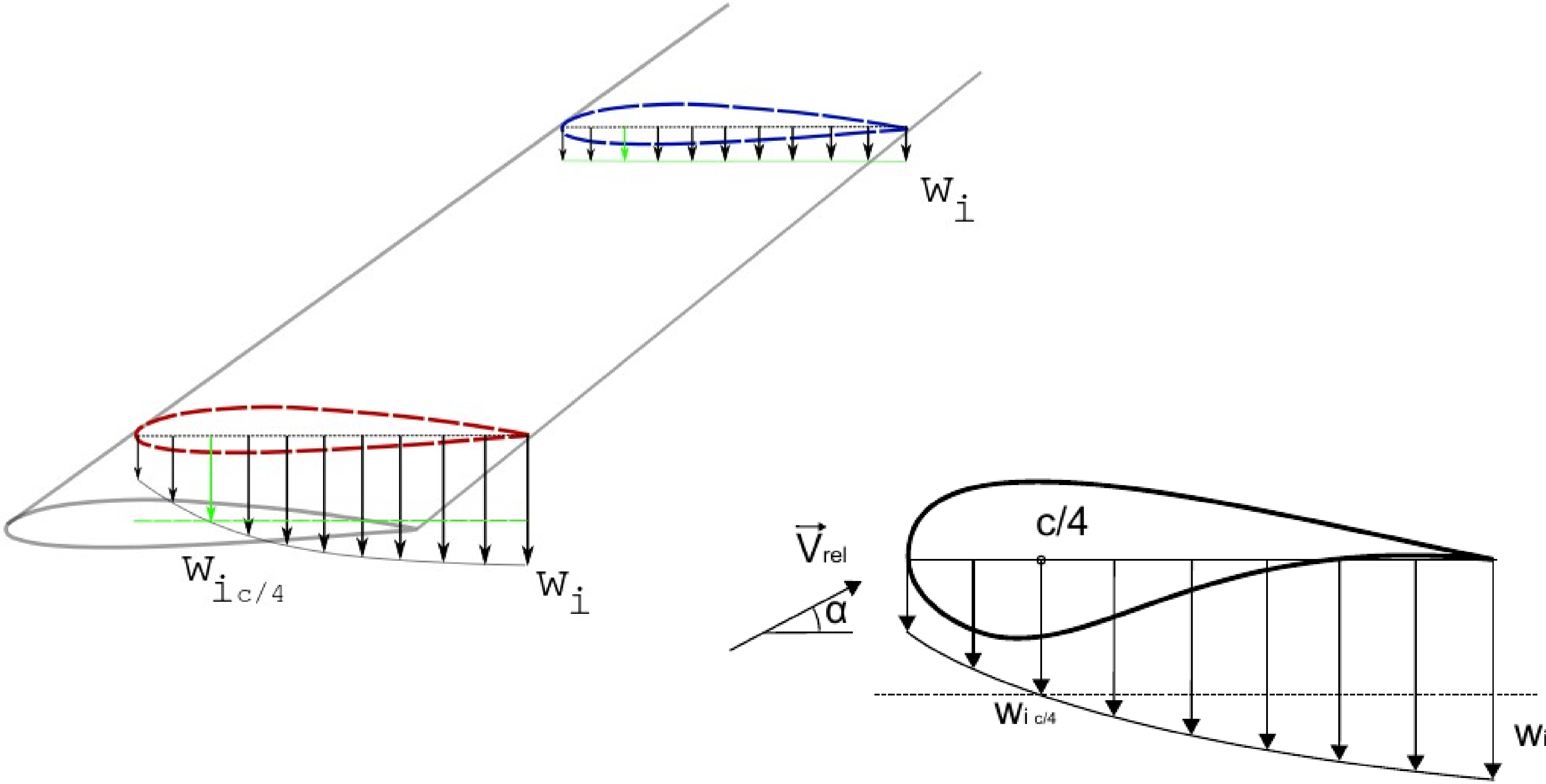
- Introduction
- The approach
- Implementation
- Comparisons with BEM and LLT applications.

Introduction



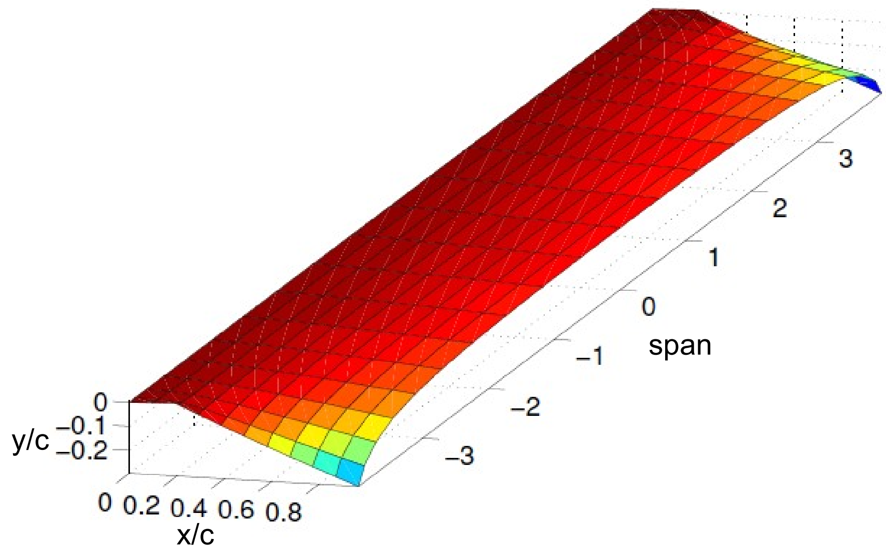
- BEM, LLT → blade is not a surface but a line
- Angle of attack represented at 1/4-chord point
- Inductions at trailing edge > leading edge
- Downwash induced by the free vortices causes curved streamlines along the chord

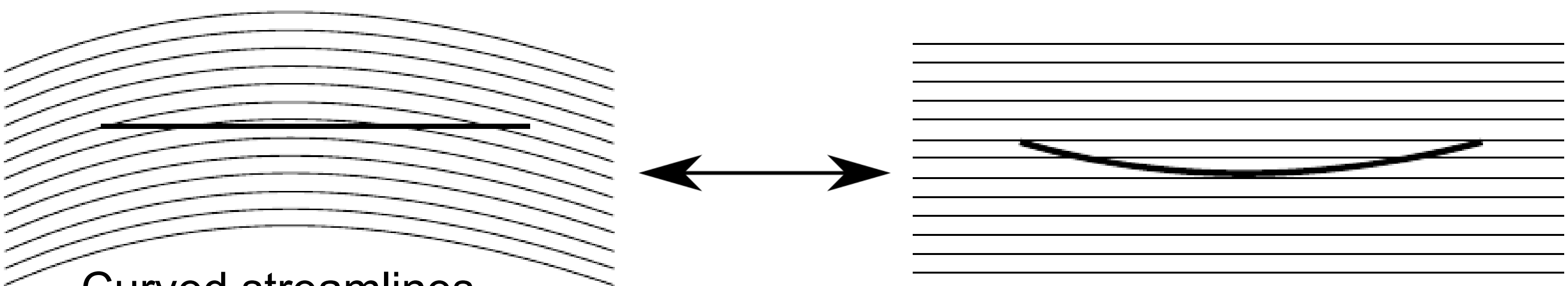
Induction from the wake



Decambering

- In the tip region, the flow is pushed downwards at the trailing edge as a result of strong vortex induction from the tip vortex
- Effect of the curved streamlines can be modeled by transfering their curvature to the airfoil section

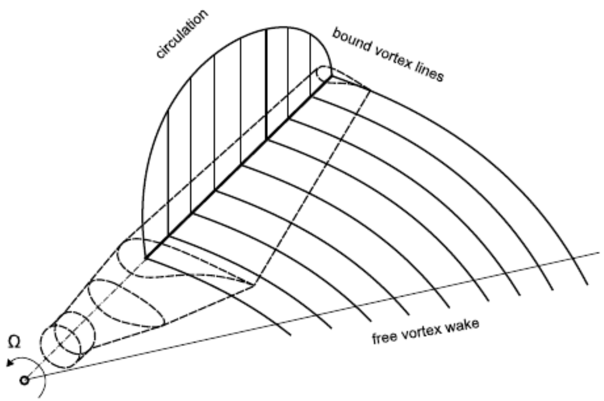


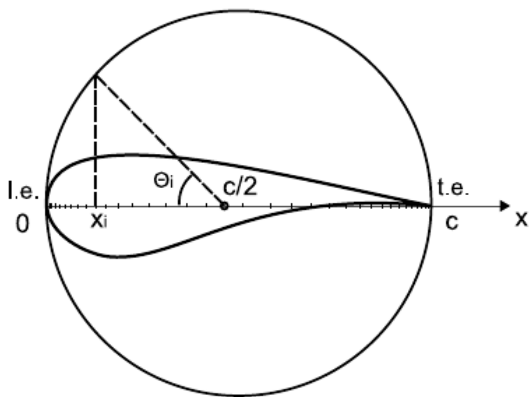


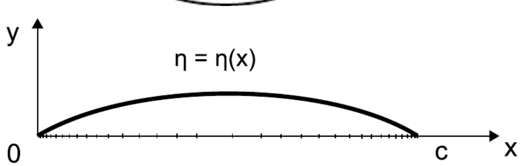
Curved streamlines representing the additional downwash

Additional downwash felt as negative bending

The correction







Biot-Savart Law

$$q = \frac{\Gamma}{4\pi}\frac{(r_1 + r_2)(\vec{r_1} \times \vec{r_2})}{r_1 r_2 (r_1 r_2 + \vec{r_1} \cdot \vec{r_2})}$$

$$w_{jk} = \sum_{i=1}^{N} a_{ijk}\Gamma_i, \quad u_{jk} = \sum_{i=1}^{N} b_{ijk}\Gamma_i$$

Induced Cambering

$$\left.\frac{d\eta}{dx}\right|_{jk} = \frac{w_{jk} - w_{j,c/4}}{||V_{rel,j}||cos\alpha_j + u_{jk} - u_{j,c/4}}$$

Thin airfoil theory

$$\alpha_{L0} = -\frac{1}{\pi}\int_0^{\pi}\frac{d\eta_c}{dx}(cos\theta - 1)d\theta$$

$$C_l = 2\pi(\alpha - \alpha_{L0})$$

$$\Delta C_{l,j} = 2\Delta\theta\sum_{k=1}^{M}\frac{(w_{jk} - w_{j,c/4})(cos\theta_k - 1)}{V_{rel,j}cos\alpha_j + (u_{jk} - u_{j,c/4})}$$

The correction

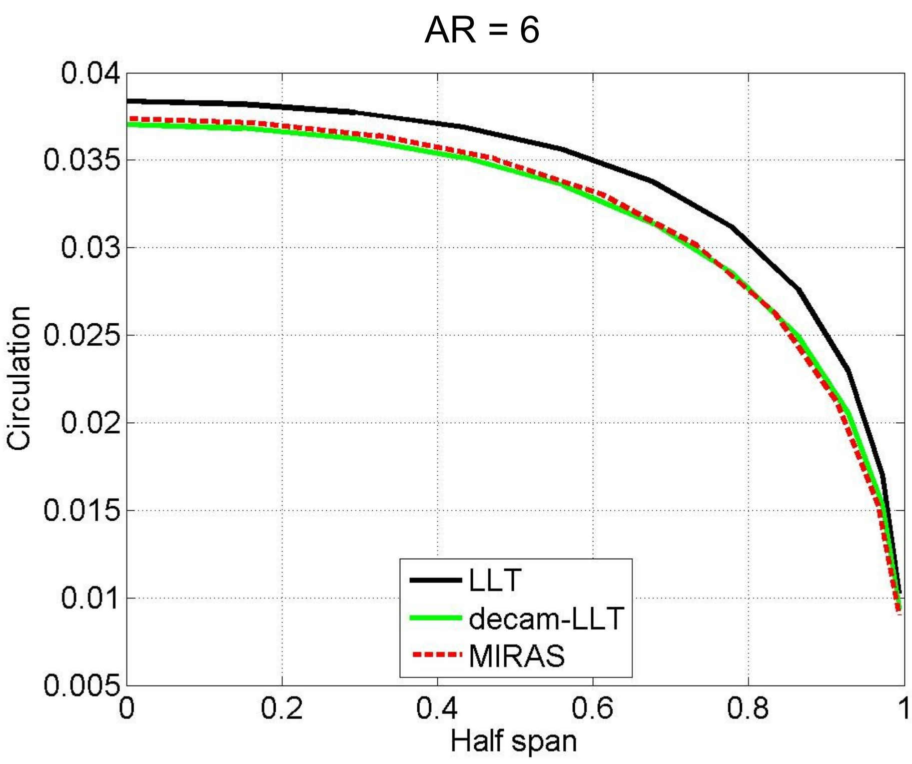
Kutta-Joukowsky theorem is employed to correct the circulation directly.

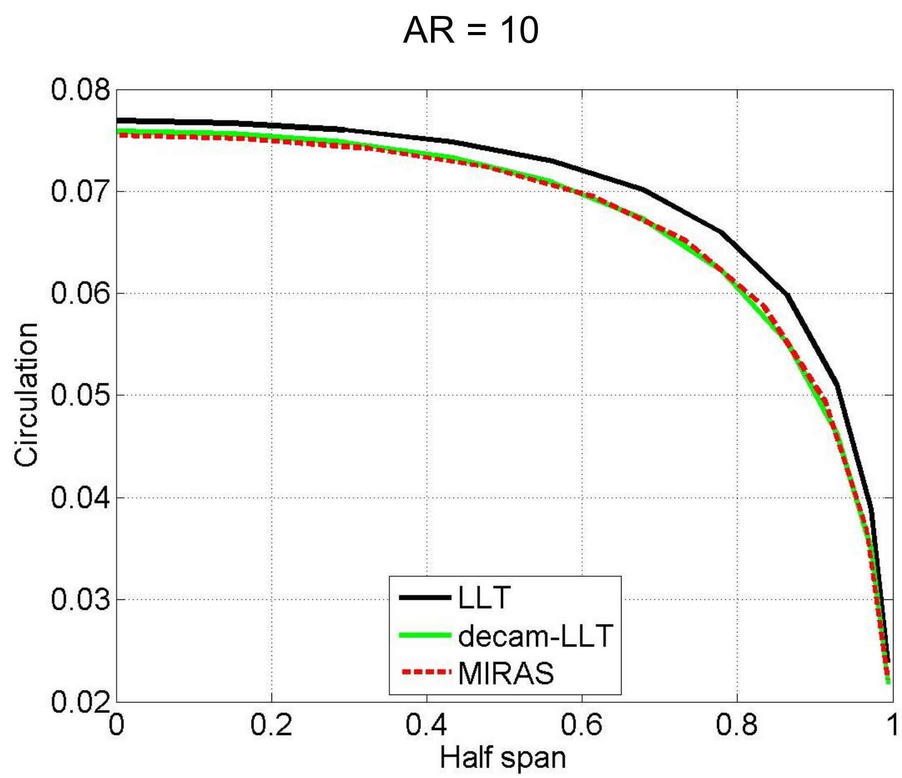
$$\Gamma = \frac{1}{2} c V_{rel} C_l$$

$$\Delta C_{l,j} = 2\Delta\theta \sum_{k=1}^{M} \frac{(w_{jk} - w_{j,c/4})(cos\theta_k - 1)}{V_{rel,j} cos\alpha_j + (u_{jk} - u_{j,c/4})}$$

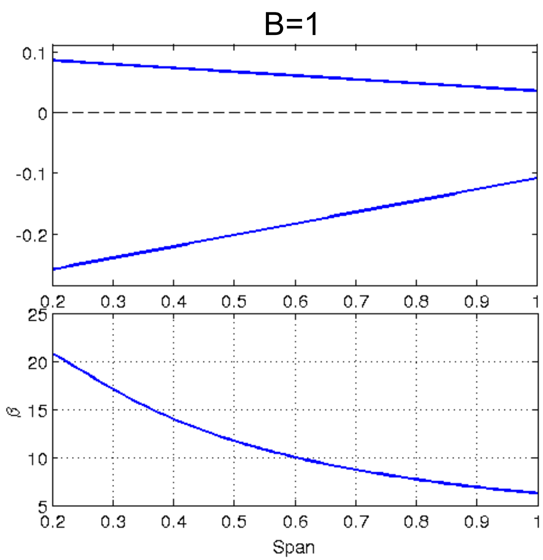
$$\Delta\Gamma_j = \frac{\Delta\theta \cdot c_j}{cos\alpha_j} \sum_{k=1}^{M} (w_{jk} - w_{j,C/2})(cos\theta - 1)$$

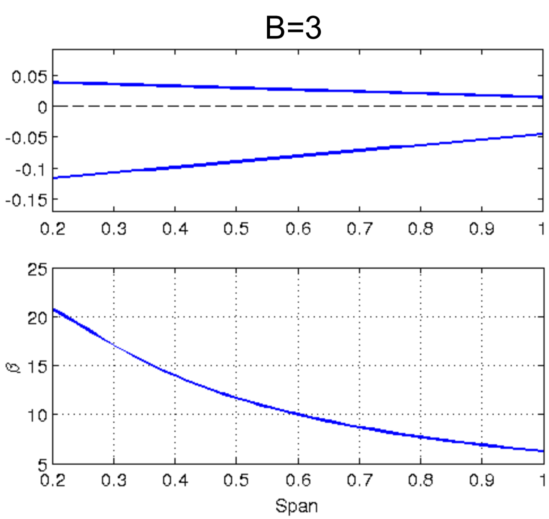
Lifting line – planar wing





Optimum rotor blades





$$C_l = 0.7$$

$$\lambda = 6$$

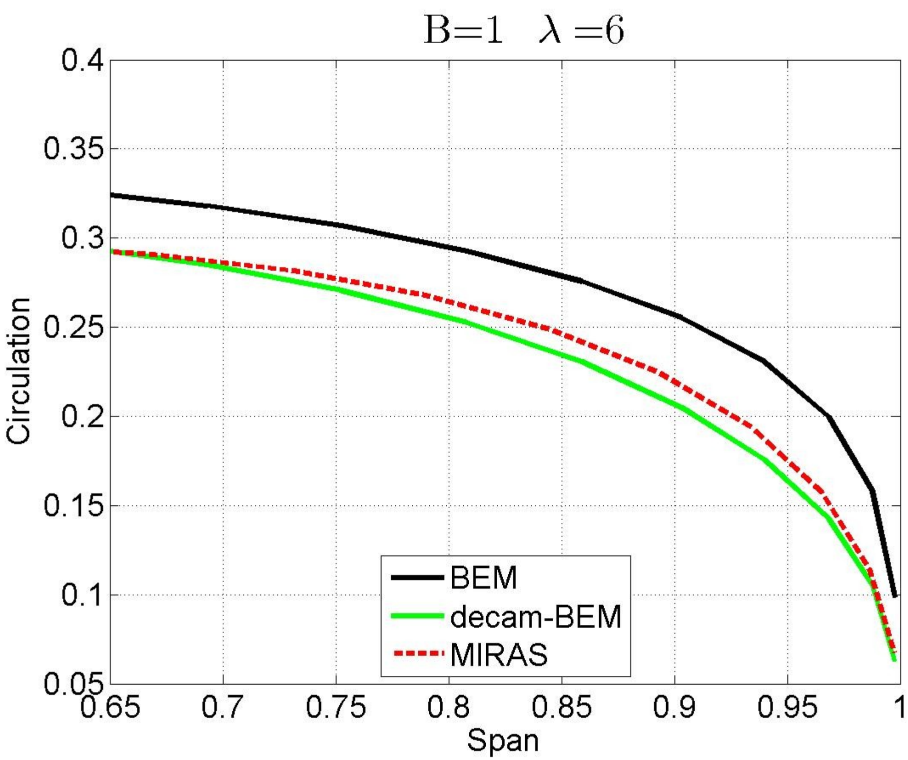
AoA $= 1.7^\circ$

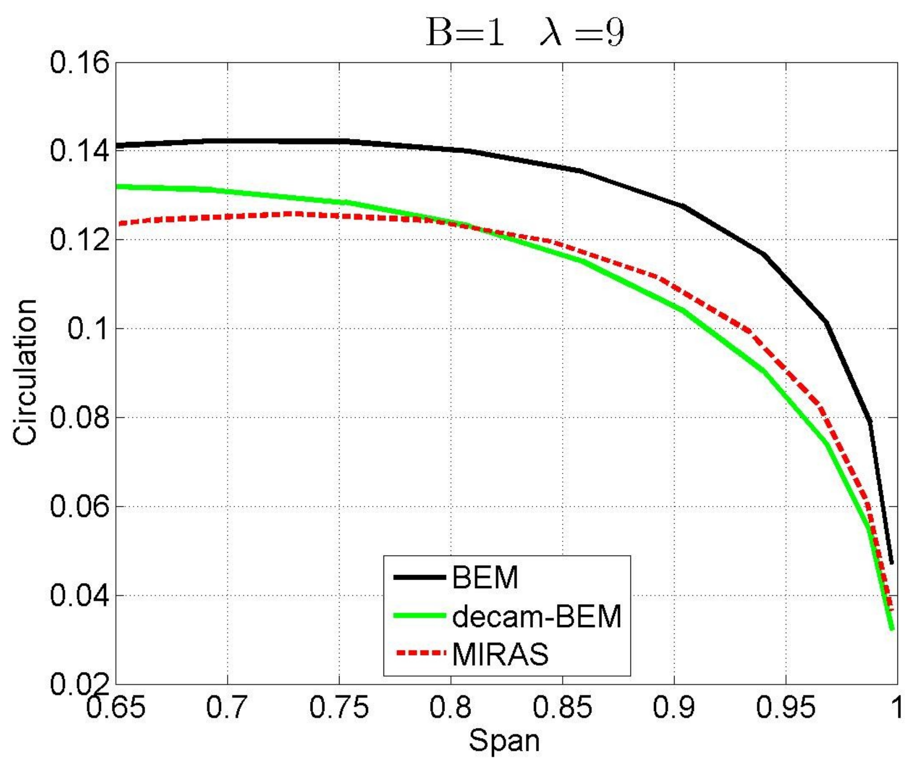
$$a_{opt} = 1/3 \qquad a'_{opt} = \frac{2}{9\lambda^2 y^2}$$

$$\beta = \tan^{-1}\left(\frac{1-a}{\lambda y(1+a')}\right)$$

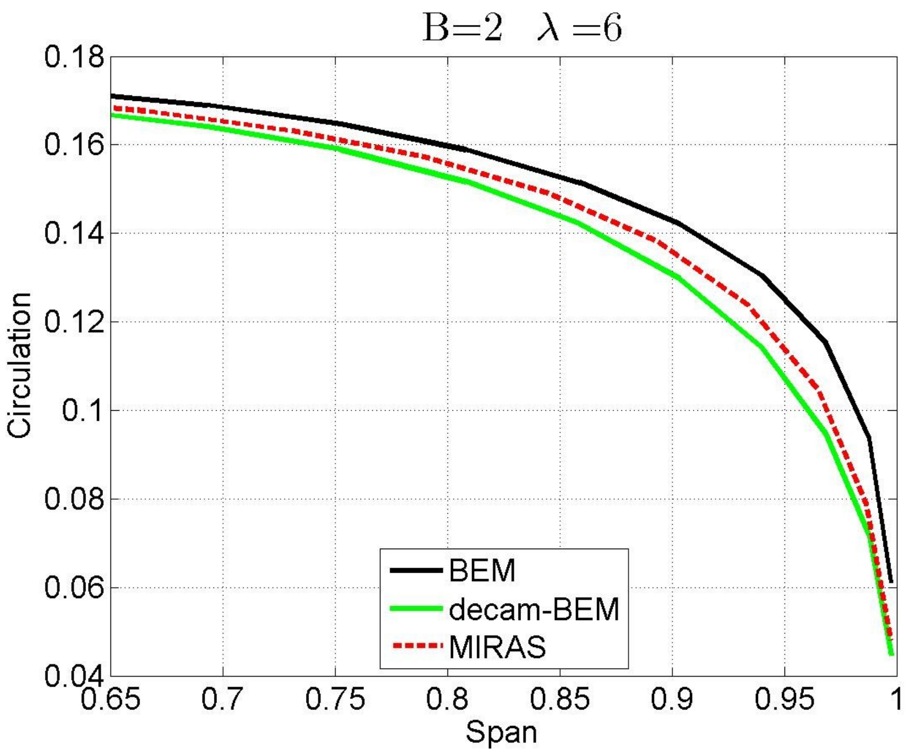
$$N_b C_l \left(\frac{c}{R}\right) = \frac{8\pi \cos\phi a'}{1+a'} y$$

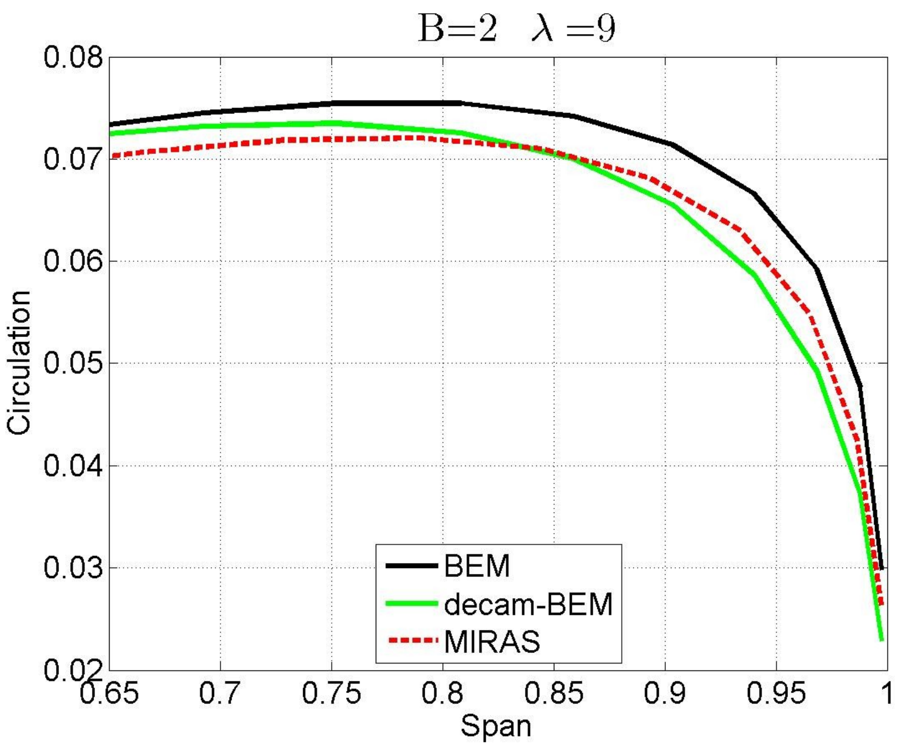
1-Bladed Rotor



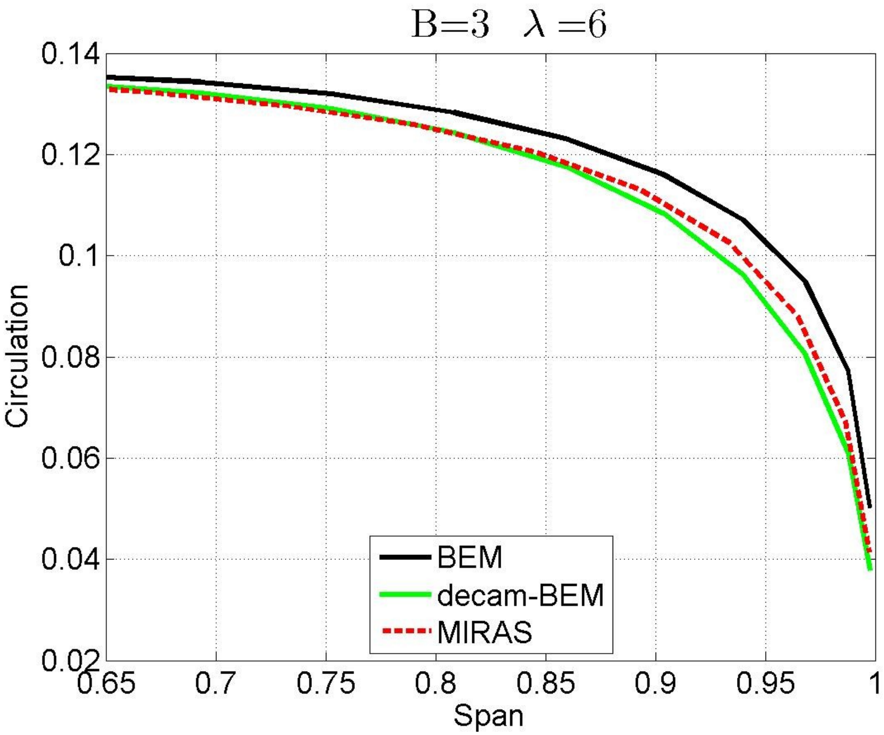


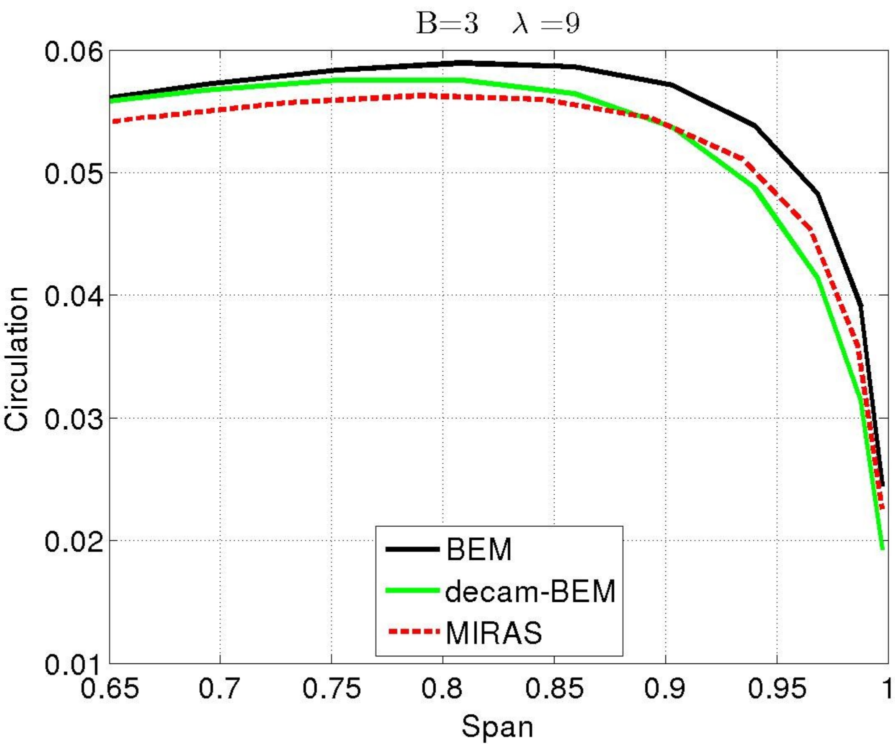
2-Bladed Rotor



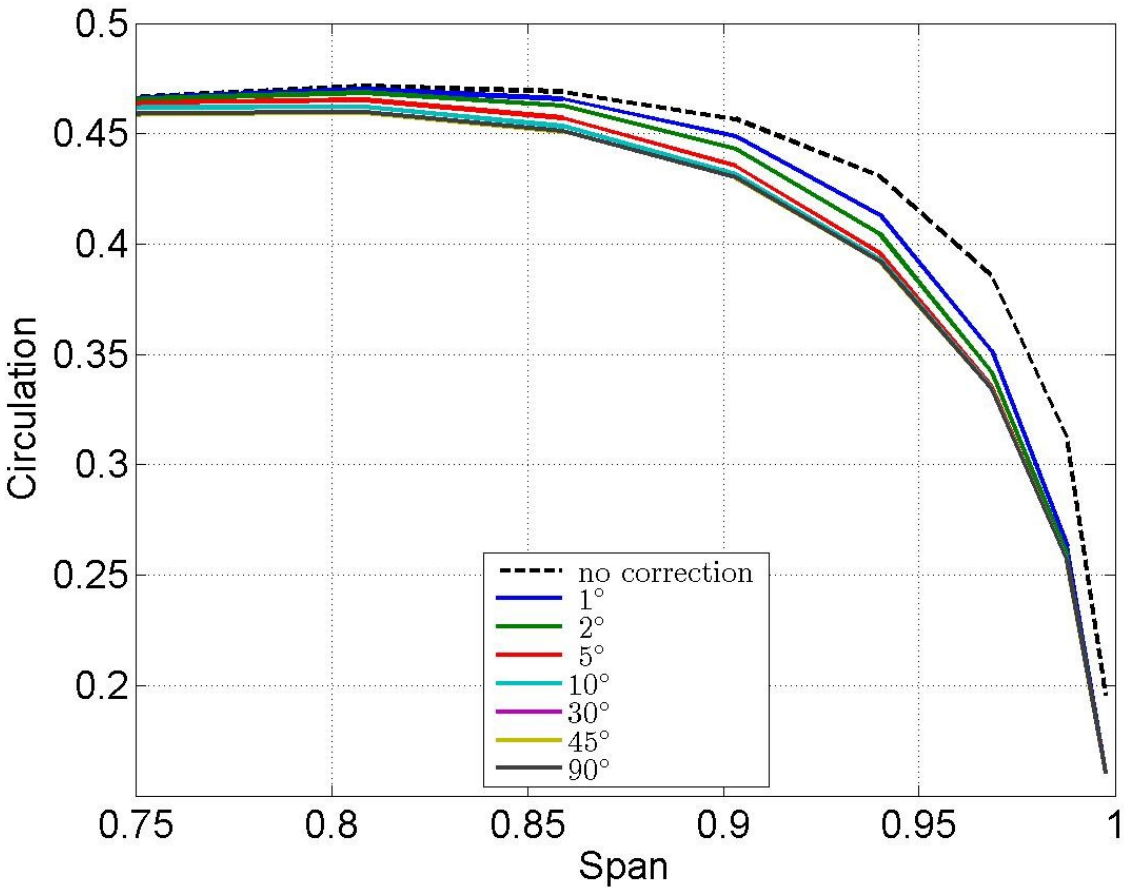


3-Bladed Rotor

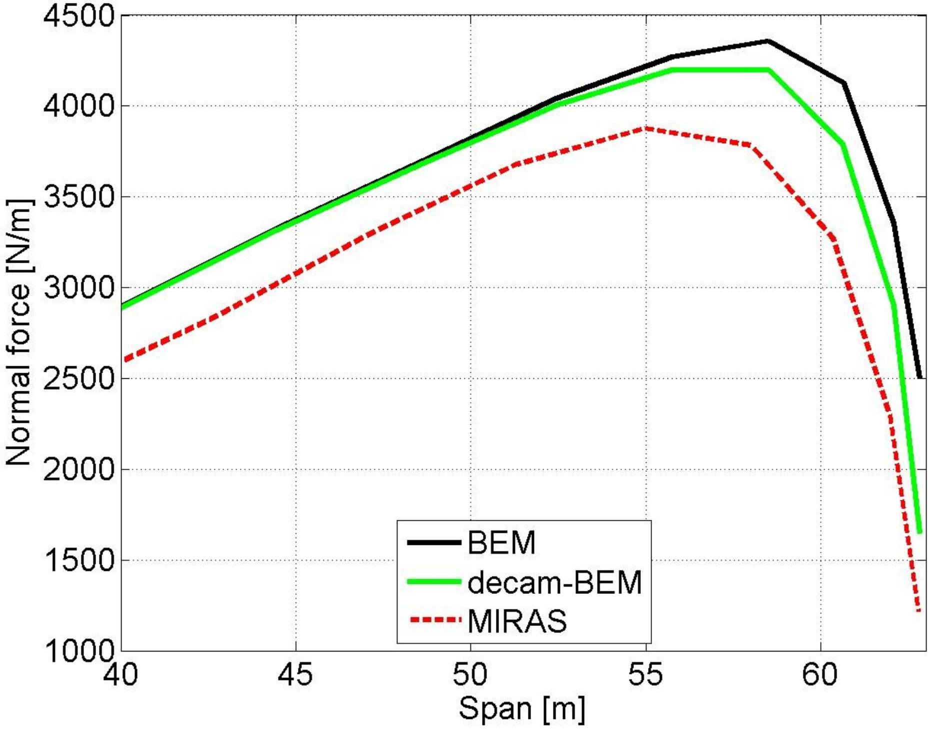


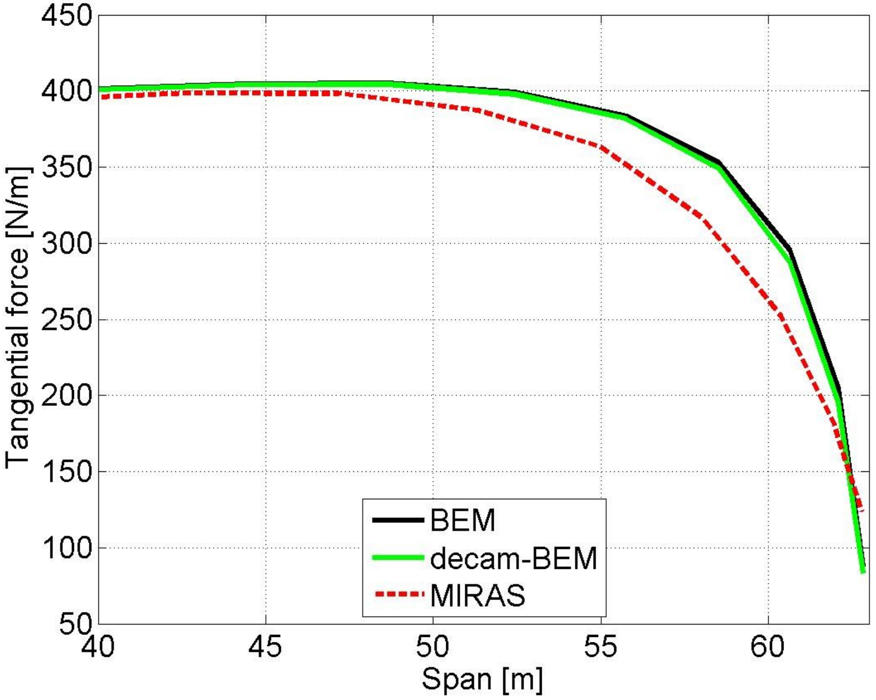


Wake length dependency



NREL 5MW Rotor @8m/s





Conclusions & future work

- Decambering effect is stronger on trapezoidal shaped blades. ~10% circulation change on a 3-bladed optimum rotor
- For NREL 5MW rotor, it is found that the new correction only has little influence on performance (~1%) and relatively high influence on thrust (~7%)
- AL implementation
- More efficient model with respect to numerical implementation.