# Efficiency of a VAWT with Airfoil Pitch Control

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# VAWT and HAWT

**VAWT**: Vertical Axis Wind Turbine

**HAWT**: Horizontal Axis Wind Turbine

# Advantages and Disadvantages

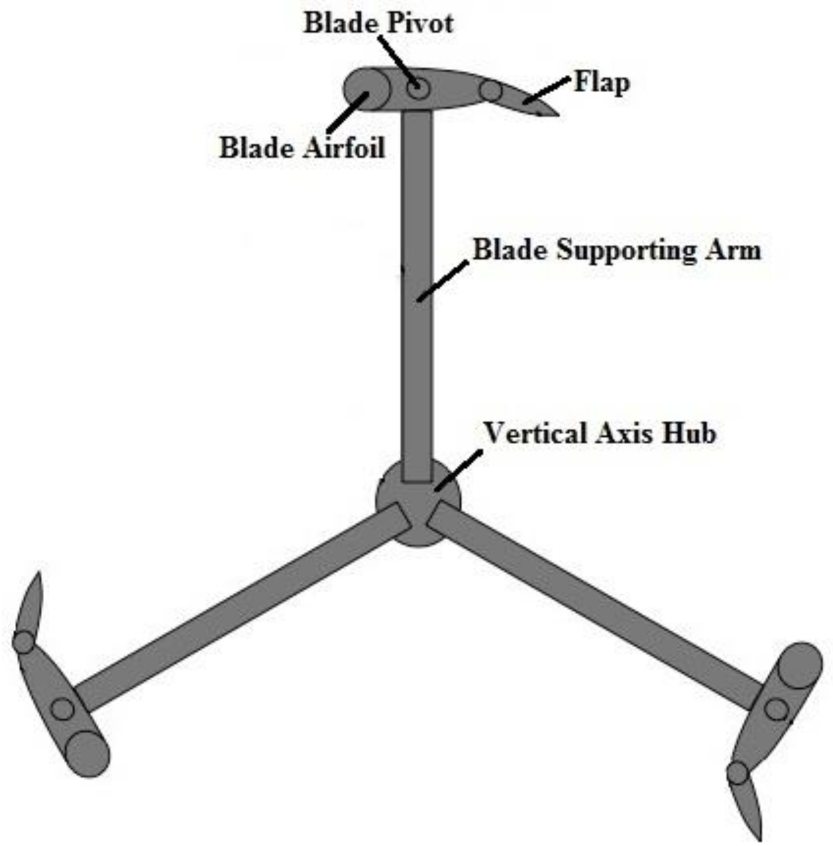
**Advantages:**

- *Easier to install and maintain*
- *No need to point into the wind*
- *Low risk for human or birds*
- *Can be installed in urban area*

**Disadvantages:**

- *Stall start*
- *Low efficiency*
- *Dynamic stability: vibration and noise*
- *Pulsatory torque*

# VAWT with Pitch and Camber Controls



# Governing Equations

## Low speed laminar flow: Navier – Stokes equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{\tau}] + \boldsymbol{F}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{T}\right) = -(\nabla \cdot \boldsymbol{q}) + \boldsymbol{\tau}{:}\,\boldsymbol{S} - \frac{T}{\rho}\frac{\partial \rho}{\partial T}\Big|_p \left(\frac{\partial p}{\partial t} + (\boldsymbol{u} \cdot \nabla)p + \boldsymbol{Q}\right)$$

## High speed turbulent flow: *κ* - *ε* turbulent flow model

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}$$

$$\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right) + P_k - \rho\varepsilon$$

$$P_k = \mu_T \left(\nabla \boldsymbol{u}{:}\,(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) - \frac{2}{3}(\nabla \cdot \boldsymbol{u})^2\right) - \frac{2}{3}\rho k \nabla \cdot \boldsymbol{u}$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \boldsymbol{u} \cdot \nabla \varepsilon = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\rho \frac{\varepsilon^2}{k}$$

| CONSTANT | VALUE |
|---|---|
| $C_\mu$ | 0.09 |
| $C_{\varepsilon 1}$ | 1.44 |
| $C_{\varepsilon 2}$ | 1.92 |
| $\sigma_k$ | 1.0 |
| $\sigma_\varepsilon$ | 1.3 |

# Force and Torque

## Force：

$$\vec{F} = \oint d\vec{F} = \oint \vec{p} * ds = \oint p * (-\vec{n}) * ds$$

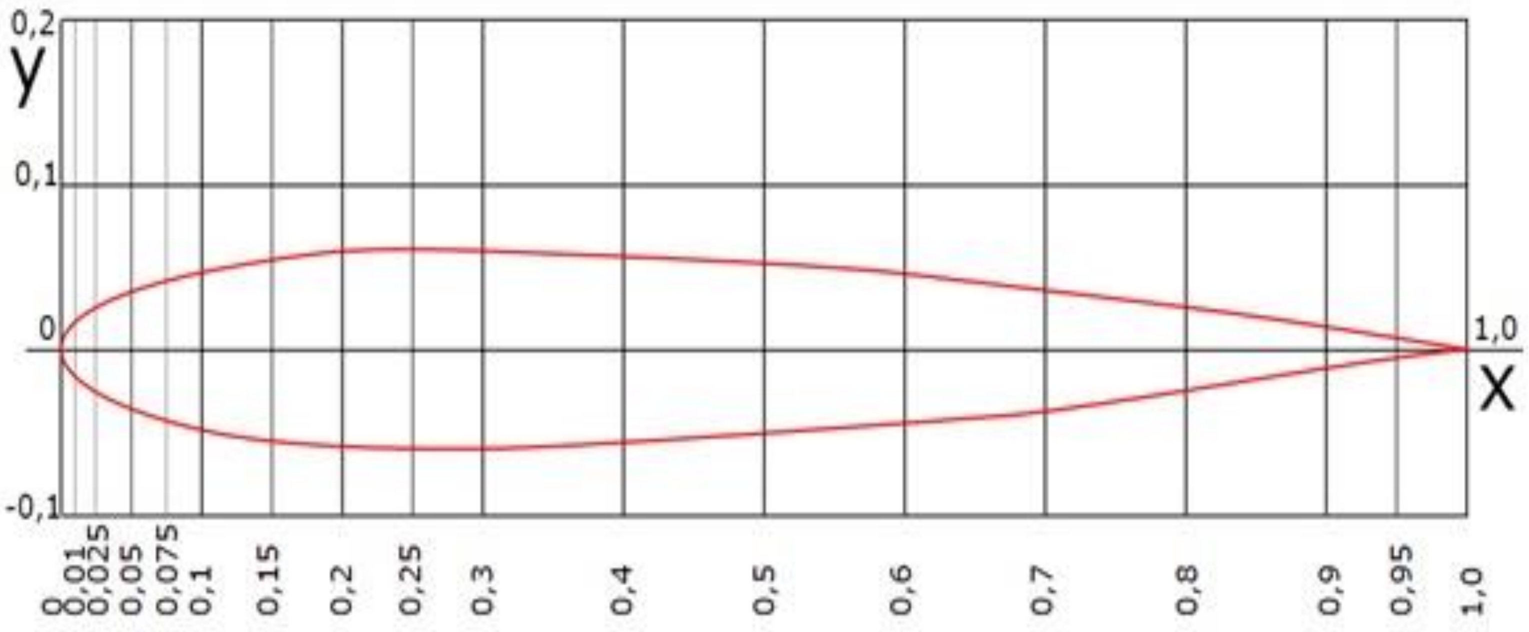
$$\vec{n} = \frac{1}{\sqrt{1^2 + (-1/y'(x))^2}}\vec{\imath} + \frac{-1/y'(x)}{\sqrt{1^2 + (-1/y'(x))^2}}\vec{\jmath}$$

$$\vec{F} = \oint p * \frac{-1}{\sqrt{1^2 + (-1/y'(x))^2}} * ds\vec{\imath} + \oint p * \frac{1/y'(x)}{\sqrt{1^2 + (-1/y'(x))^2}} * ds\vec{\jmath}$$

## Torque：

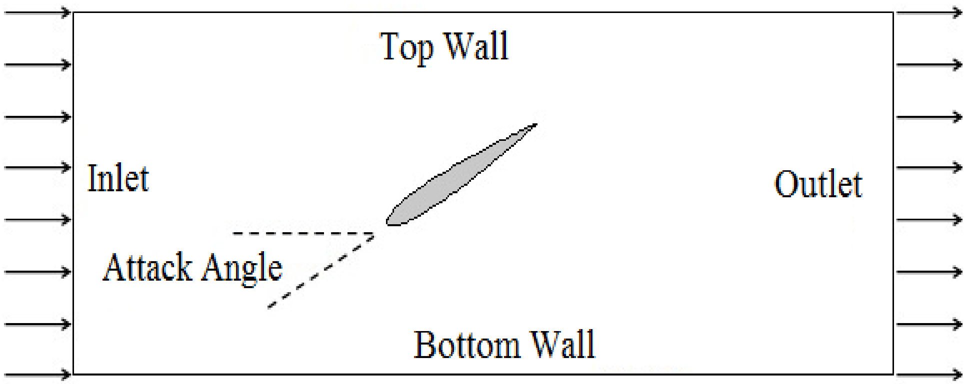
$$\vec{T} = \oint d\vec{T} = \oint \vec{r} \otimes d\vec{F}$$

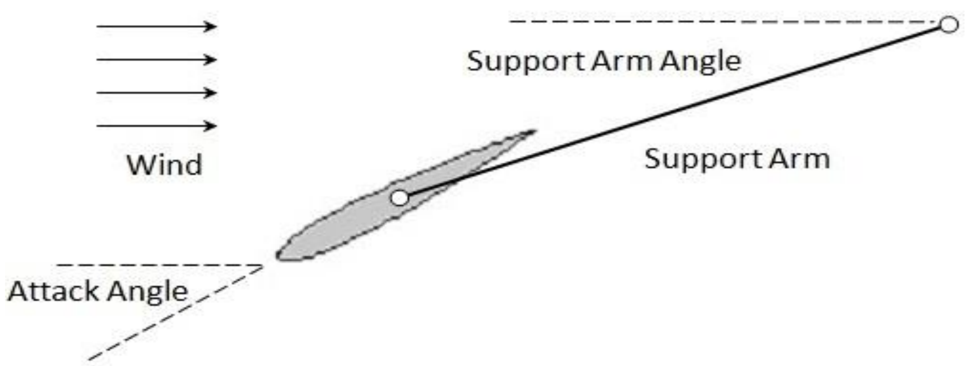
# NACA 0012 Airfoil



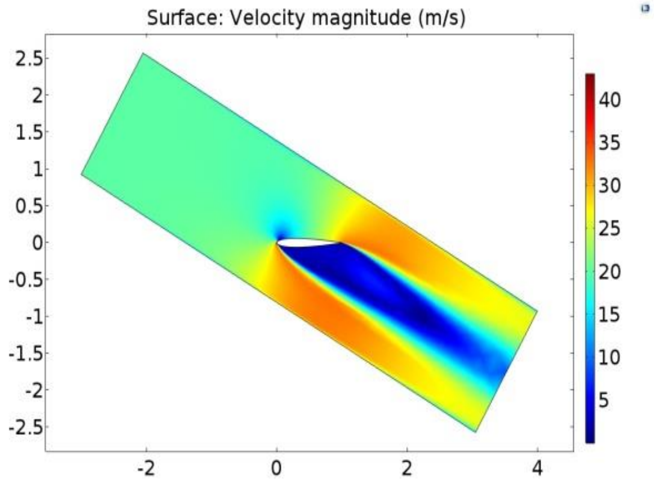

$$y = \pm 0.6\left[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right]$$

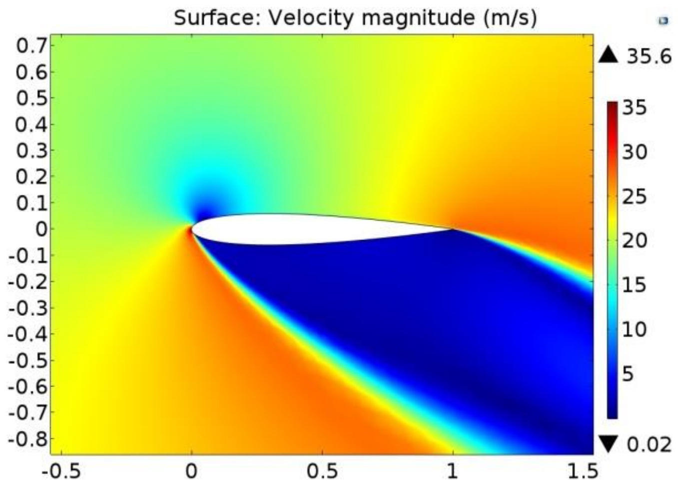
# COMSOL CFD Model

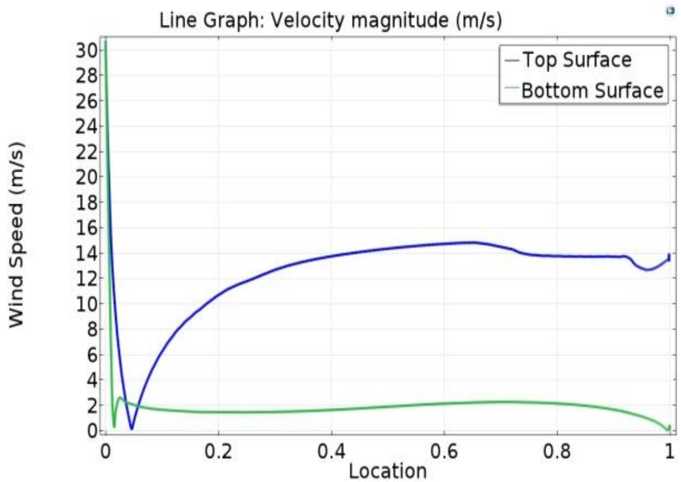


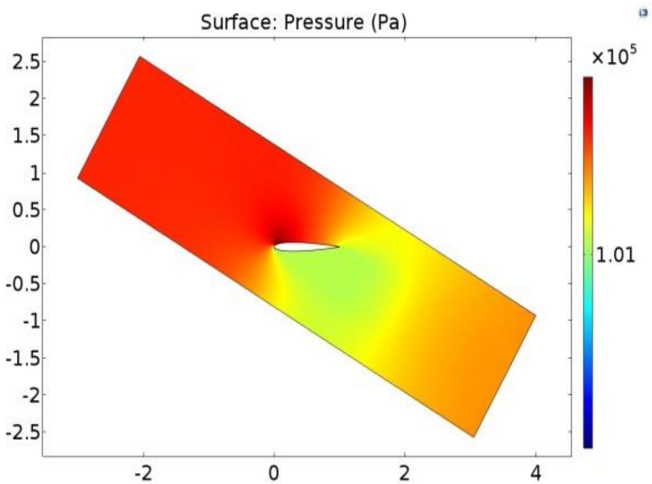
# Velocity Field

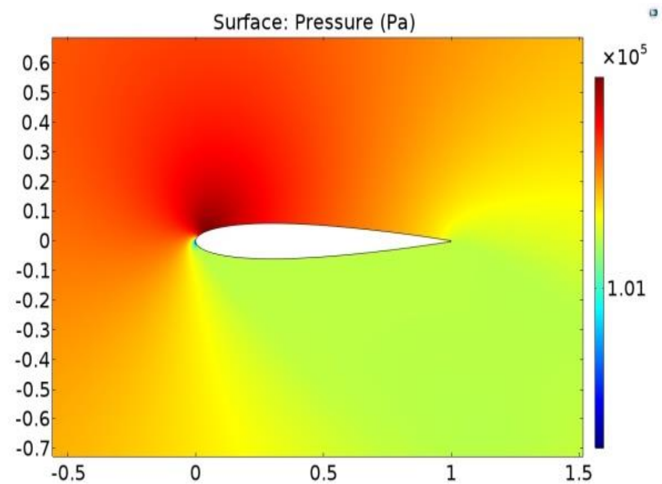


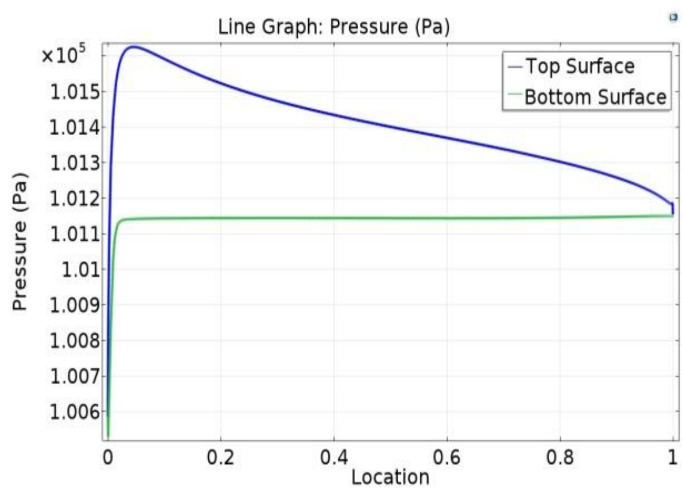



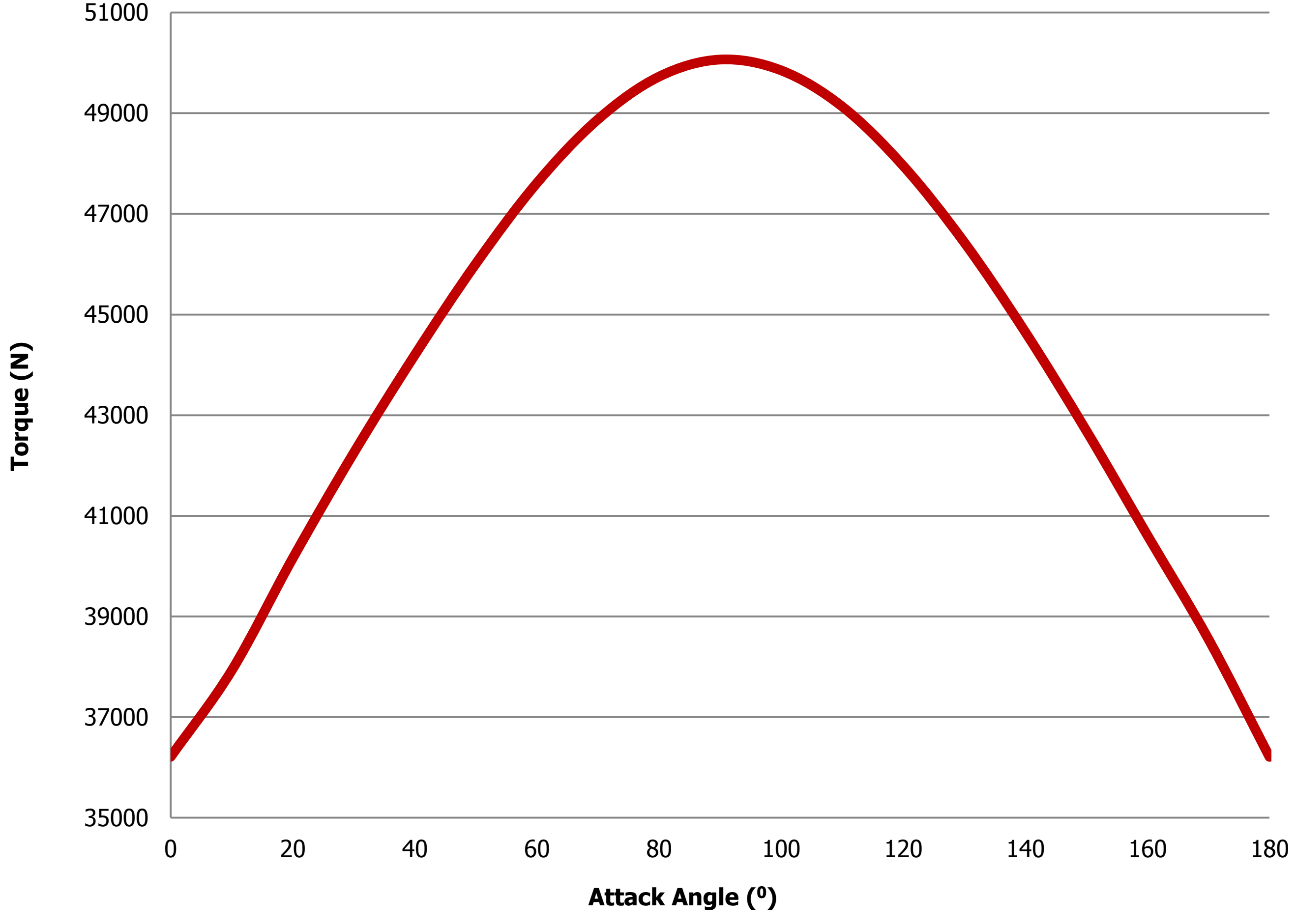
# Pressure Field



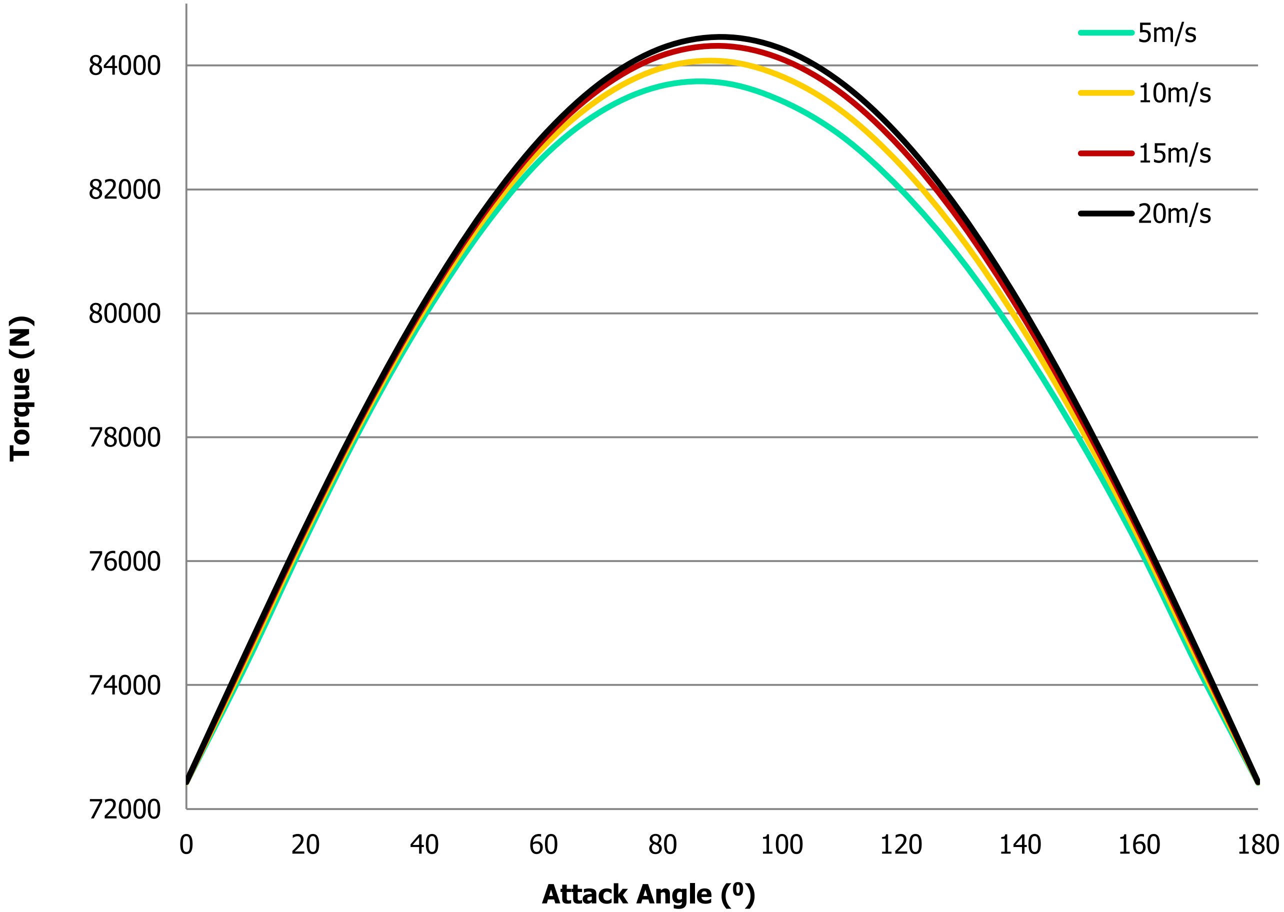



# Torque at $30^0$ Support Arm Angle



# Effects of Wind Speed



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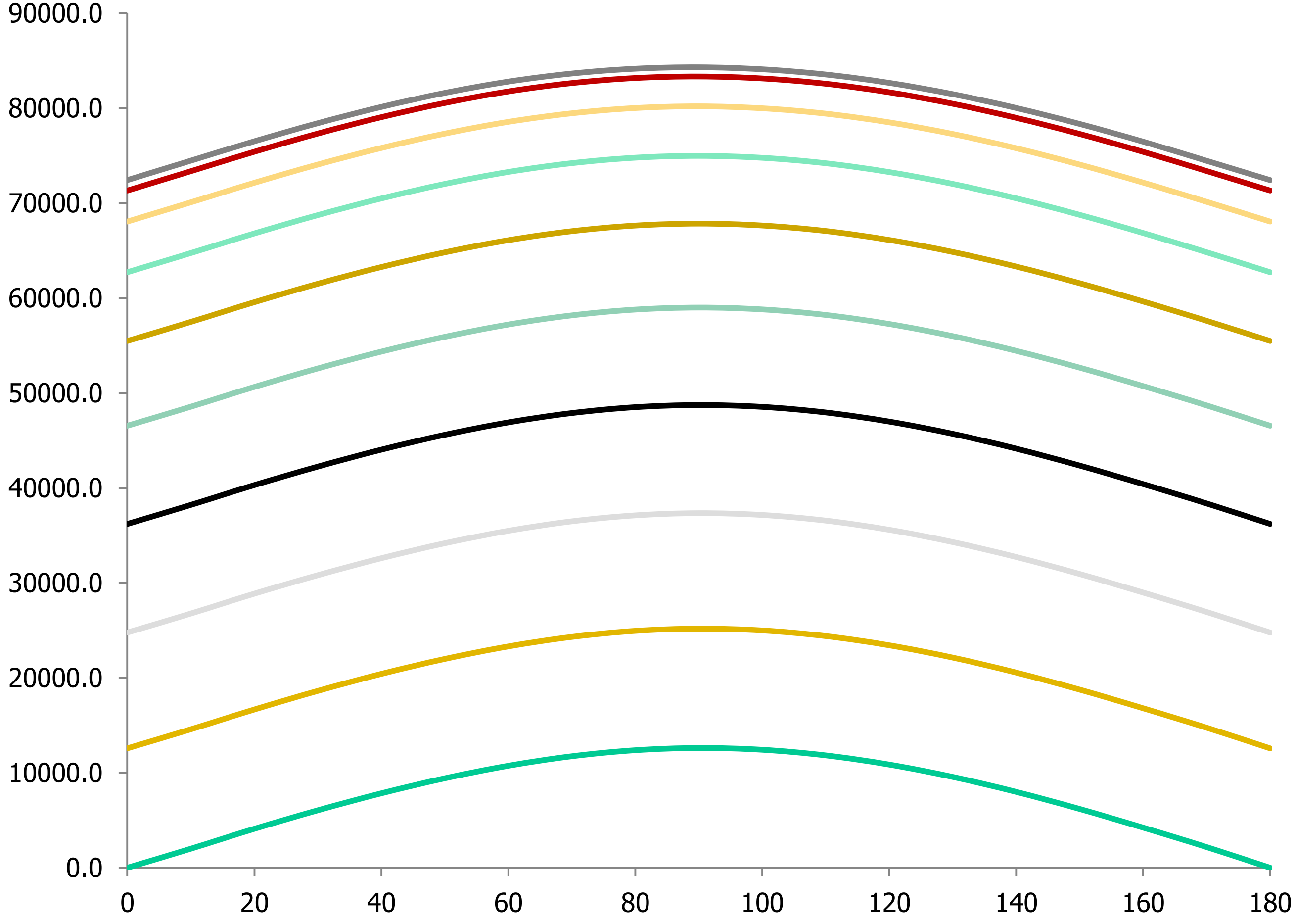

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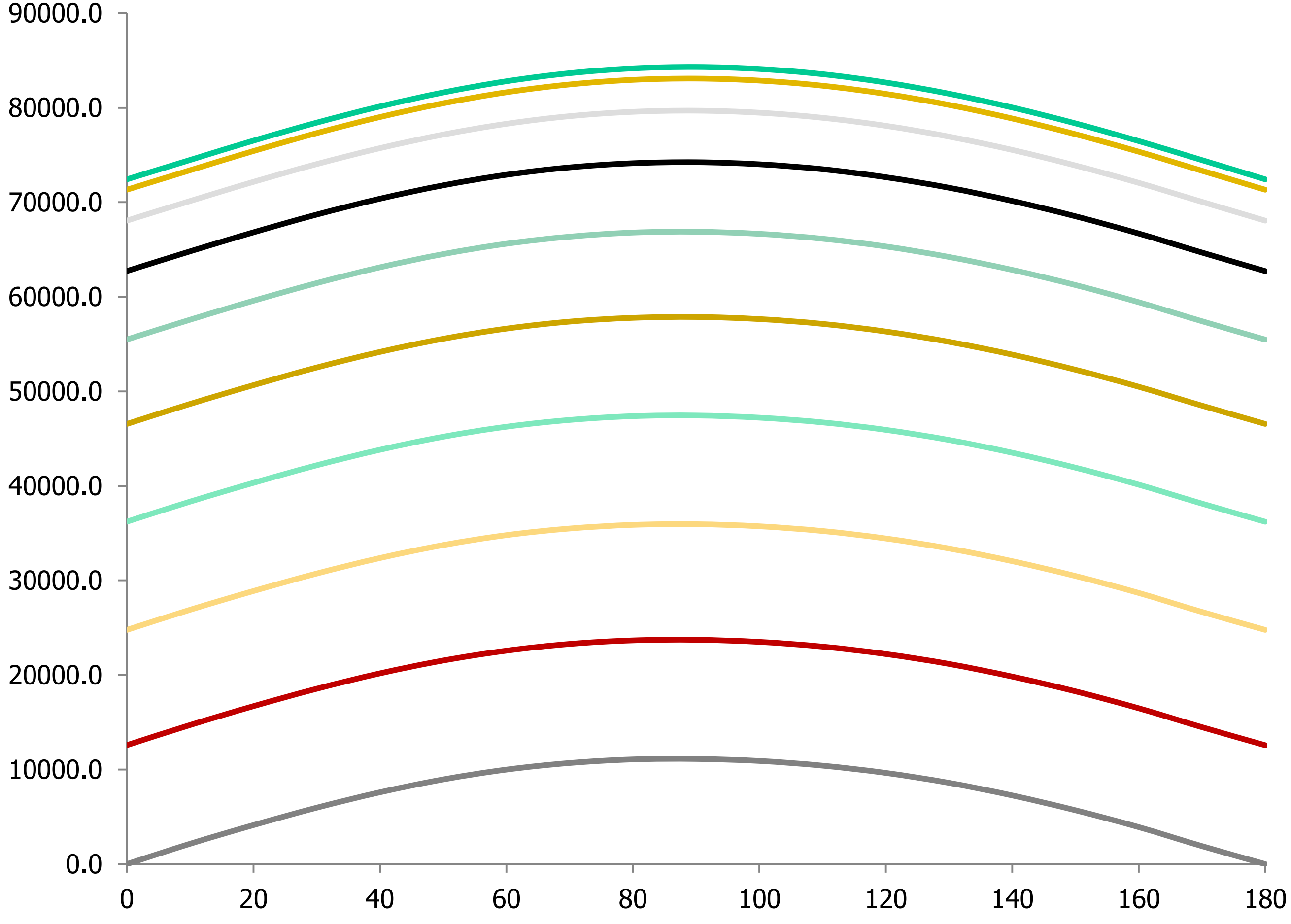

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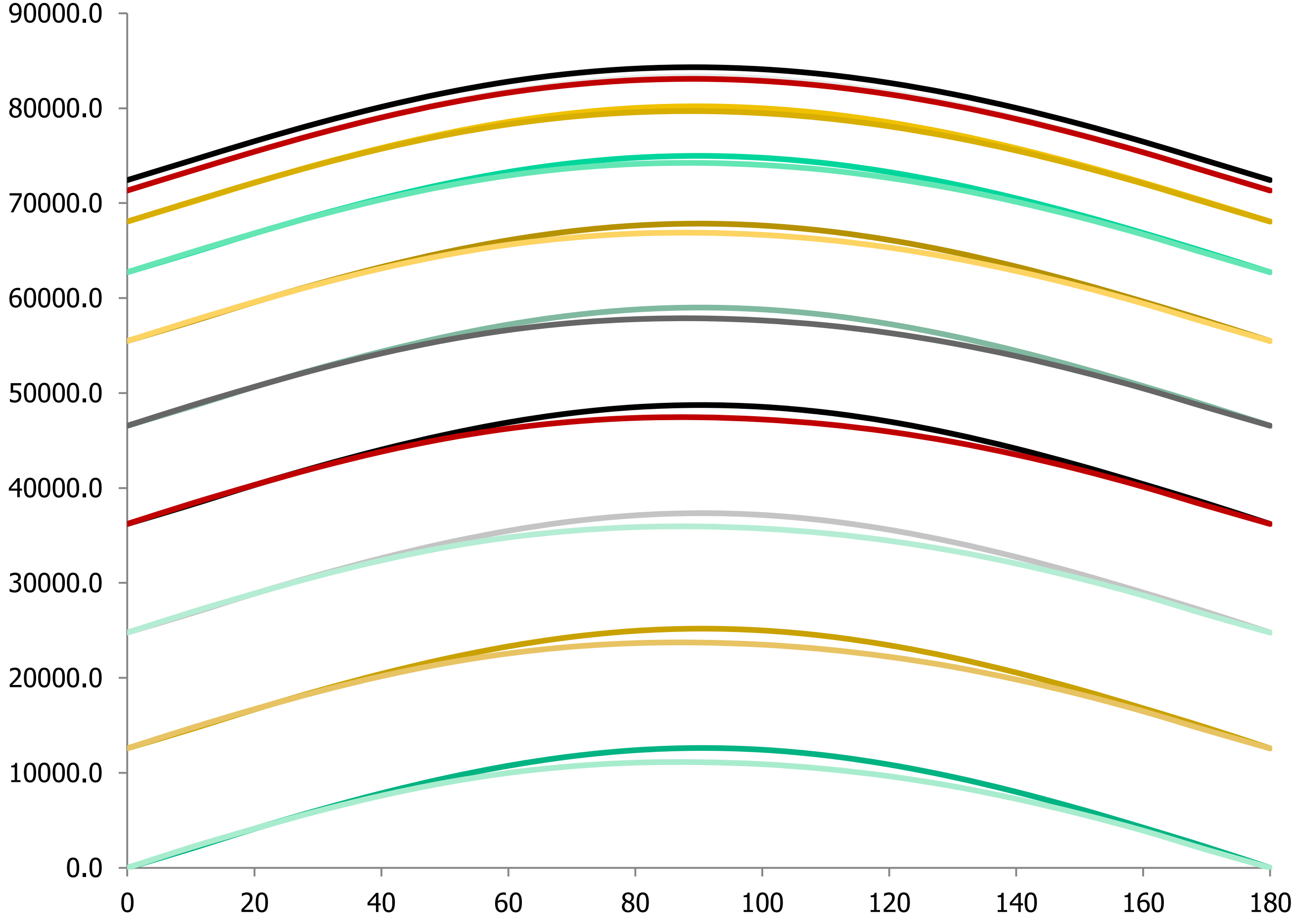

# Conclusions

- ***Torque with respect to the VAWT main rotor shaft depends on wind angle of attack and support arm angle***
- ***Wind speed does affect the peak torque. But the torque increase due to higher wind speed is insignificant***
- ***For the NACA 0012 airfoil, the torque always peaks out at 90 degree angle of attack at any given support arm angle***

# Future Work

- *2D multi-blades model*
- *3D model to explore airfoil edge effect*
- *3D multi-blades model*
- *Non-symmetric airfoil other than NACA 0012*

# Questions?