Vertical Axis Wind Turbines

Are We Any Better Informed?

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- From the mid-1970s,experimental development of **vertical axis wind turbines** (VAWTs) was underpinned by an incremental improvements of aerodynamic performance prediction methods ☺

- The **double actuator disk, multiple streamtube theory**(DMST)with corrections for streamtube expansion, dynamic stall, blade tip effects and flow curvature was the state-of-the-art and was easier to implement than the computationally more demanding vortex methods

Introduction – The Early Years

- Commercially, VAWTs have not been as successful as the three-bladed, pitch controlled horizontal axis turbine became the standard for the industry and **progress in VAWT development stagnated** ☹
- However, a **renewed interest in VAWTs** has emerged, prompted by the development of small turbines for use in urban environments and perceived advantages for large offshore turbines

Introduction – More Recently

The objective today is to:

- Present trade studies of VAWTs using the double actuator disk, multiple streamtube theory

- Look at some recent third party findings

- Present some initial VAWT investigations using a proprietary CFD software tool that uses a mesh-less approach to fluid dynamics modelling

Objective

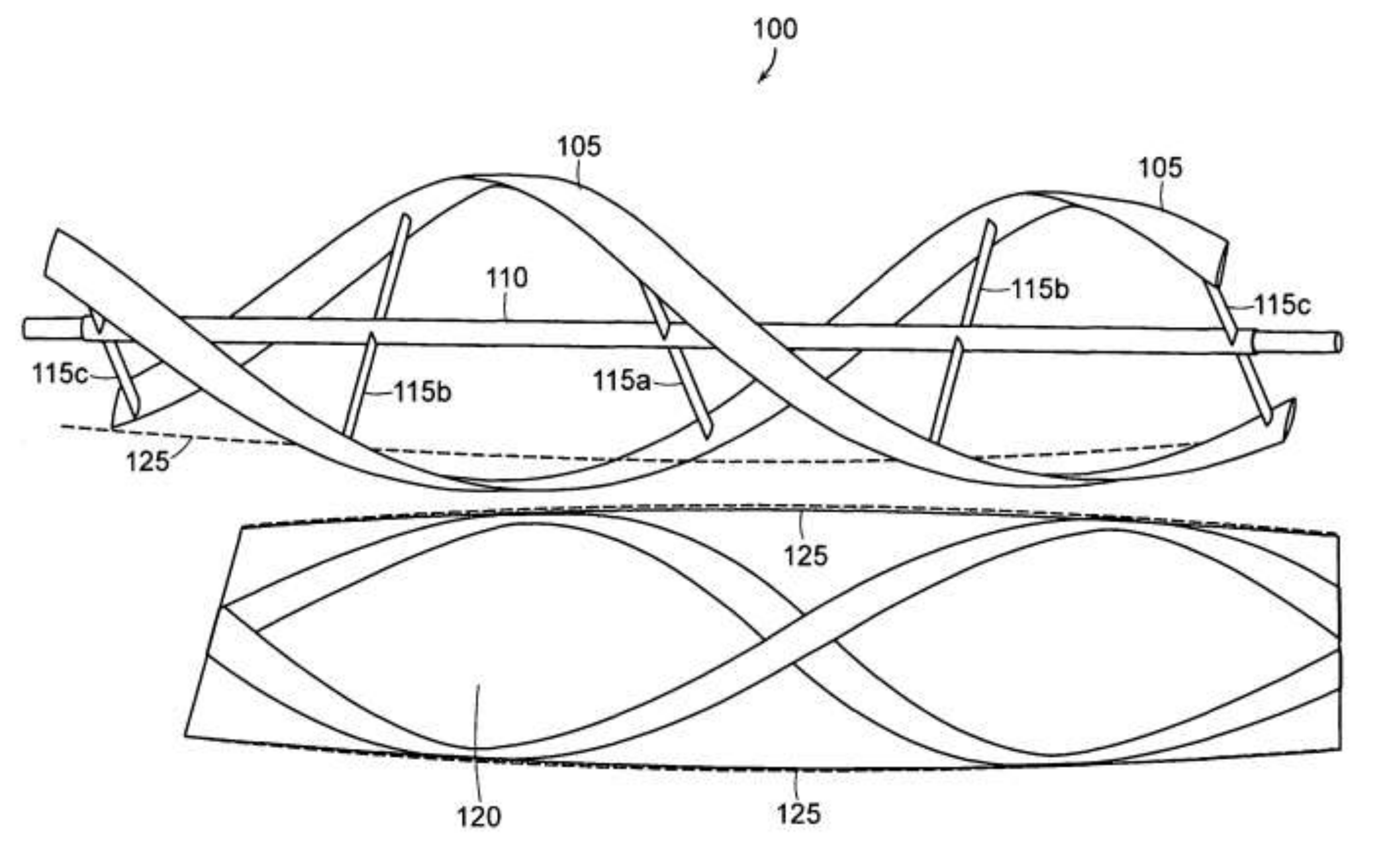
VAWTS

- Renewed interest in VAWTs for urban and offshore applications

- New generations of VAWT favour the helical configuration

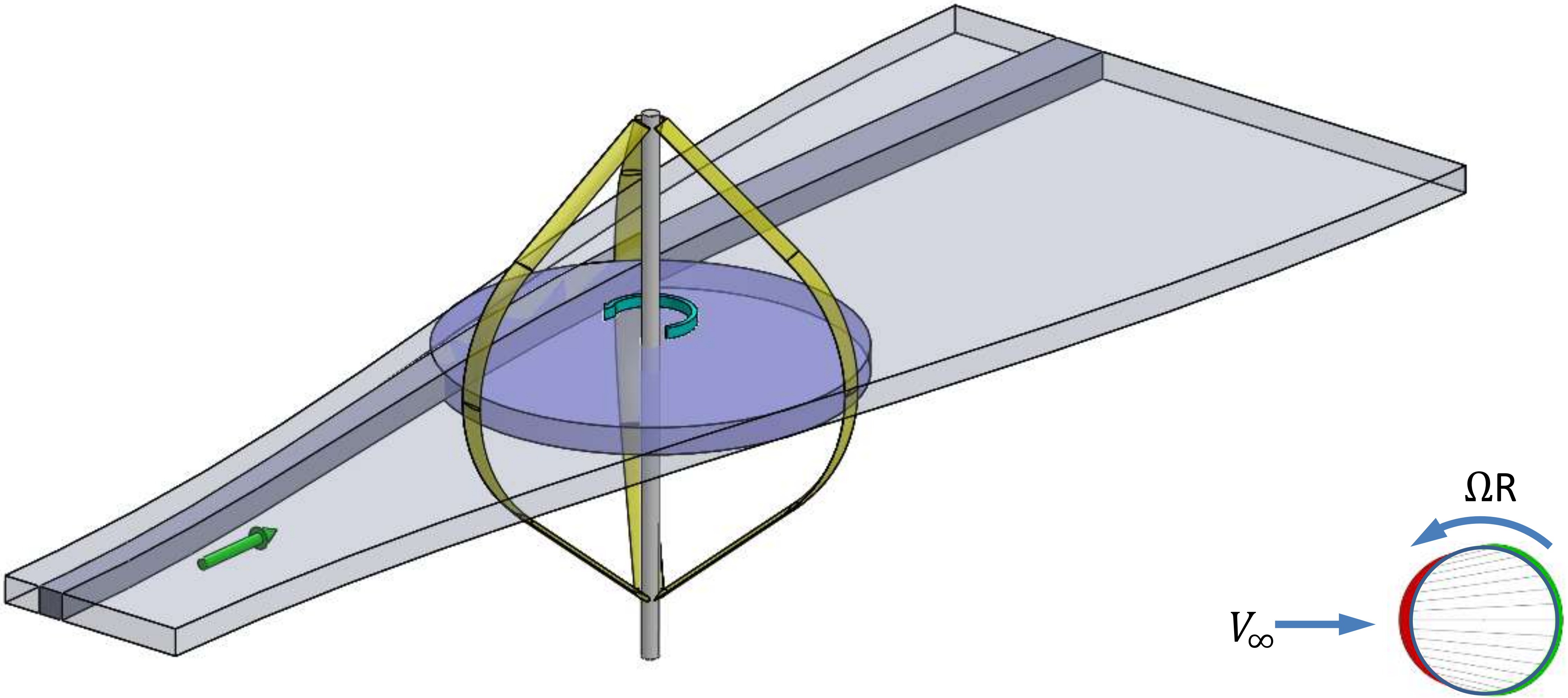
- Helical VAWTs are being designed with large height/diameter ratios

Observations



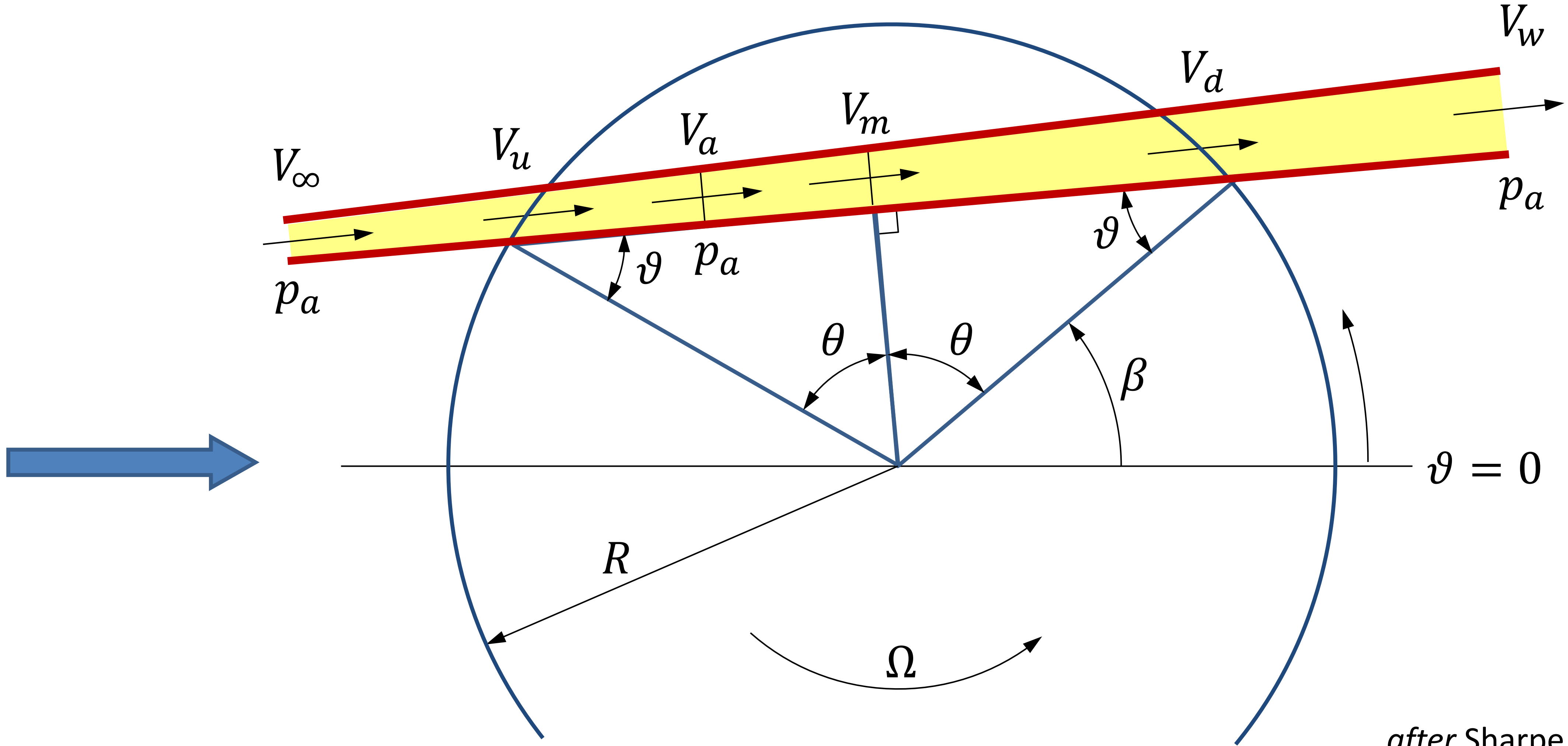
WHY HELICAL VAWTS?

What does VAWT theory tell us ?



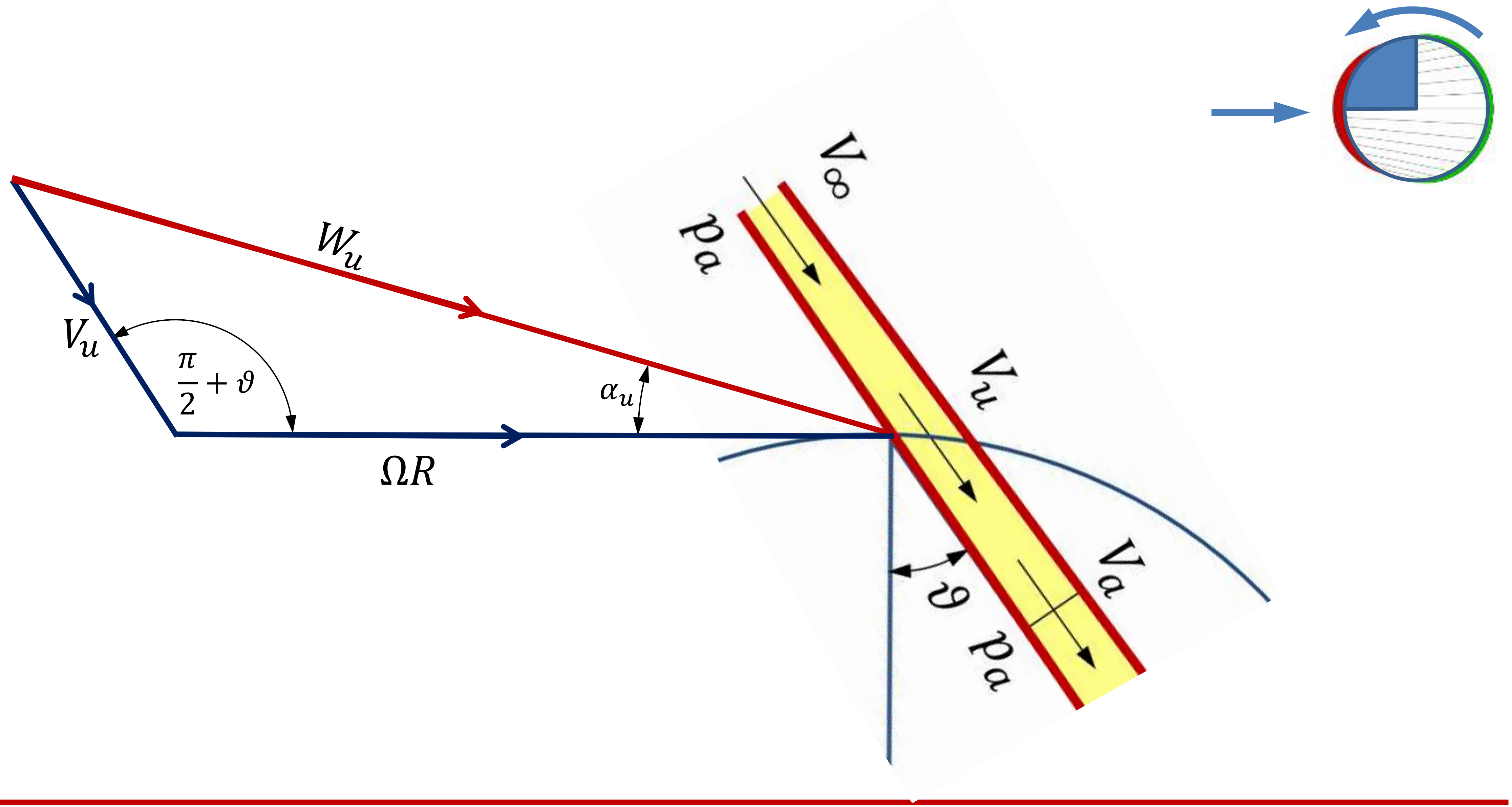
VAWT Multiple Streamtube Theory

The streamtube is bounded by streamlines at $\boldsymbol{\vartheta}$ *and* $\boldsymbol{\vartheta + \delta\vartheta}$

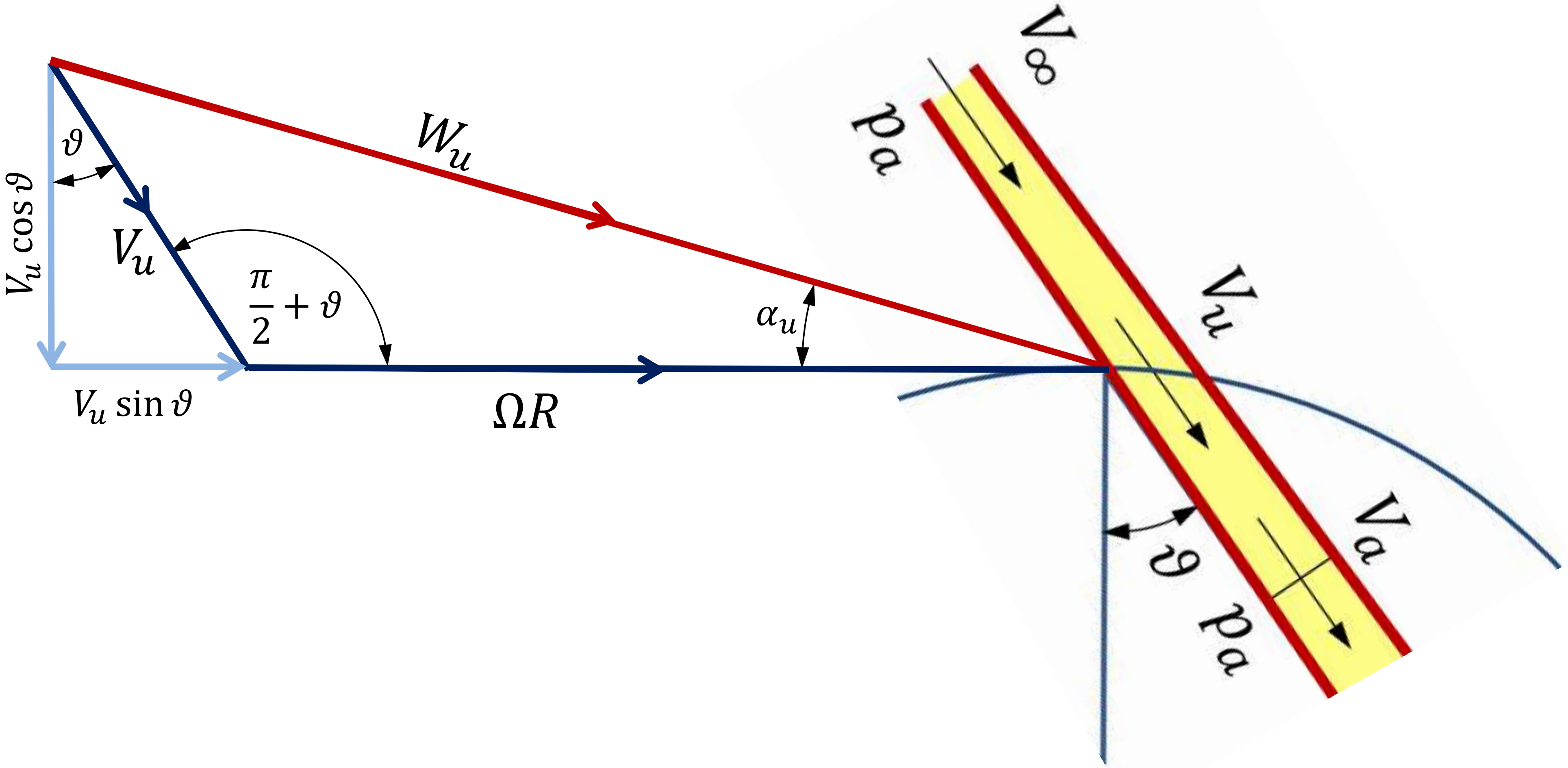


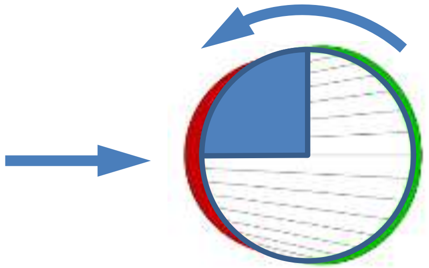
after Sharpe & Read (1982)

VAWT Streamtube

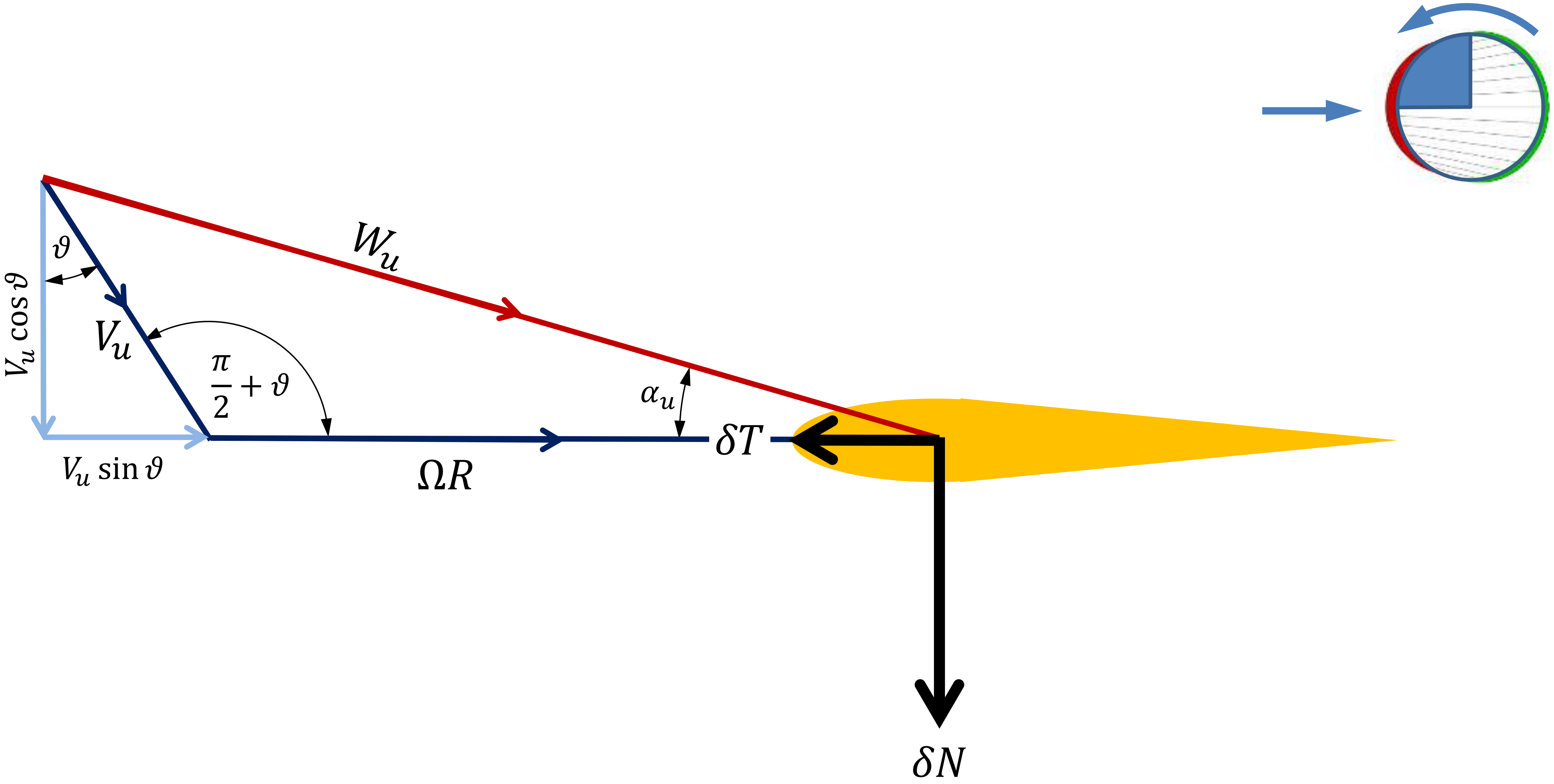


Upstream Relative Velocity Triangle

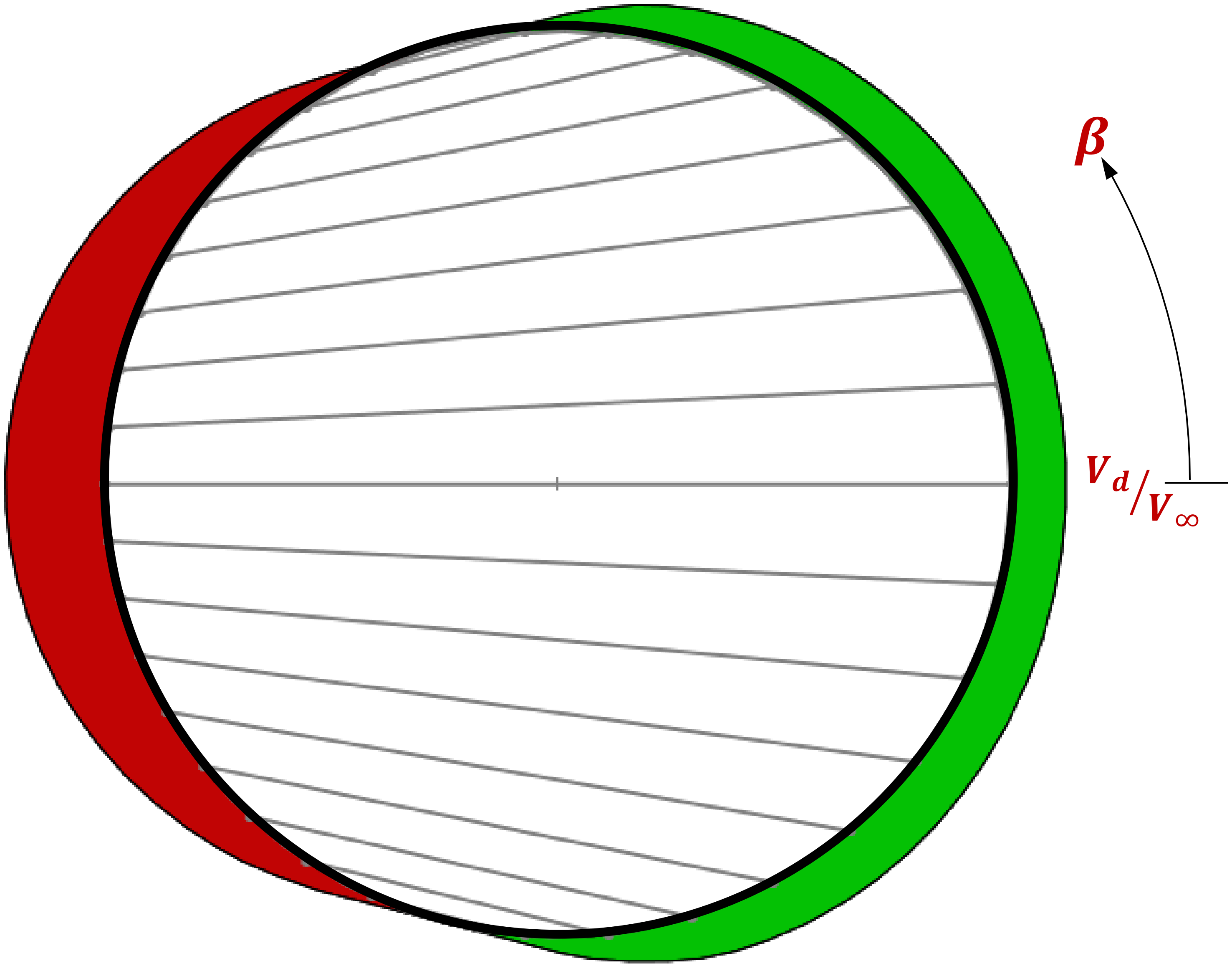




Upstream Relative Velocity Triangle



Upstream Relative Velocity Triangle



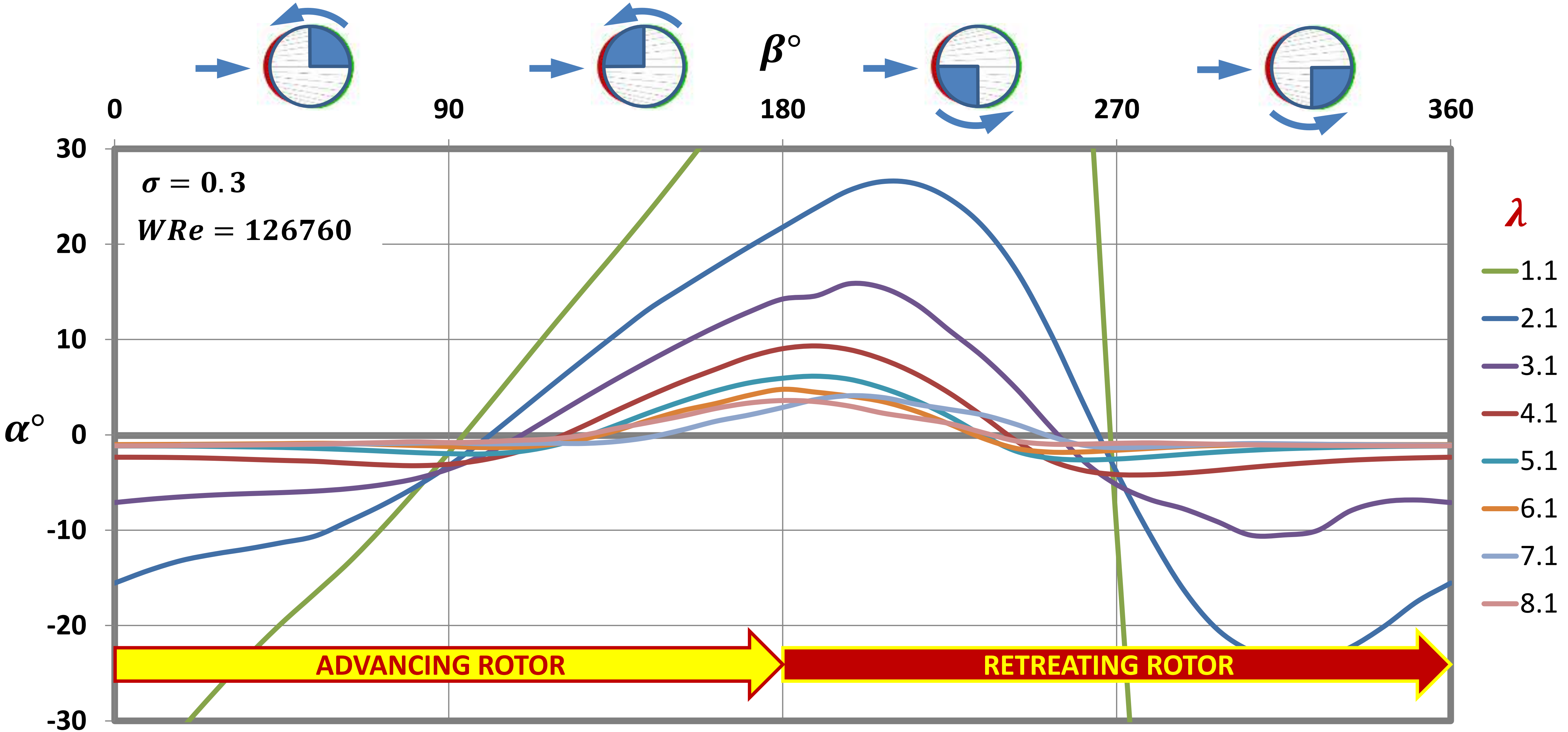
$$C_{p_{max}} = 0.522 \;\; at \;\; k = 0.358$$

$$where\ k = \frac{a\sigma}{4\pi}\left(\frac{\Omega R}{V_\infty}\right)$$

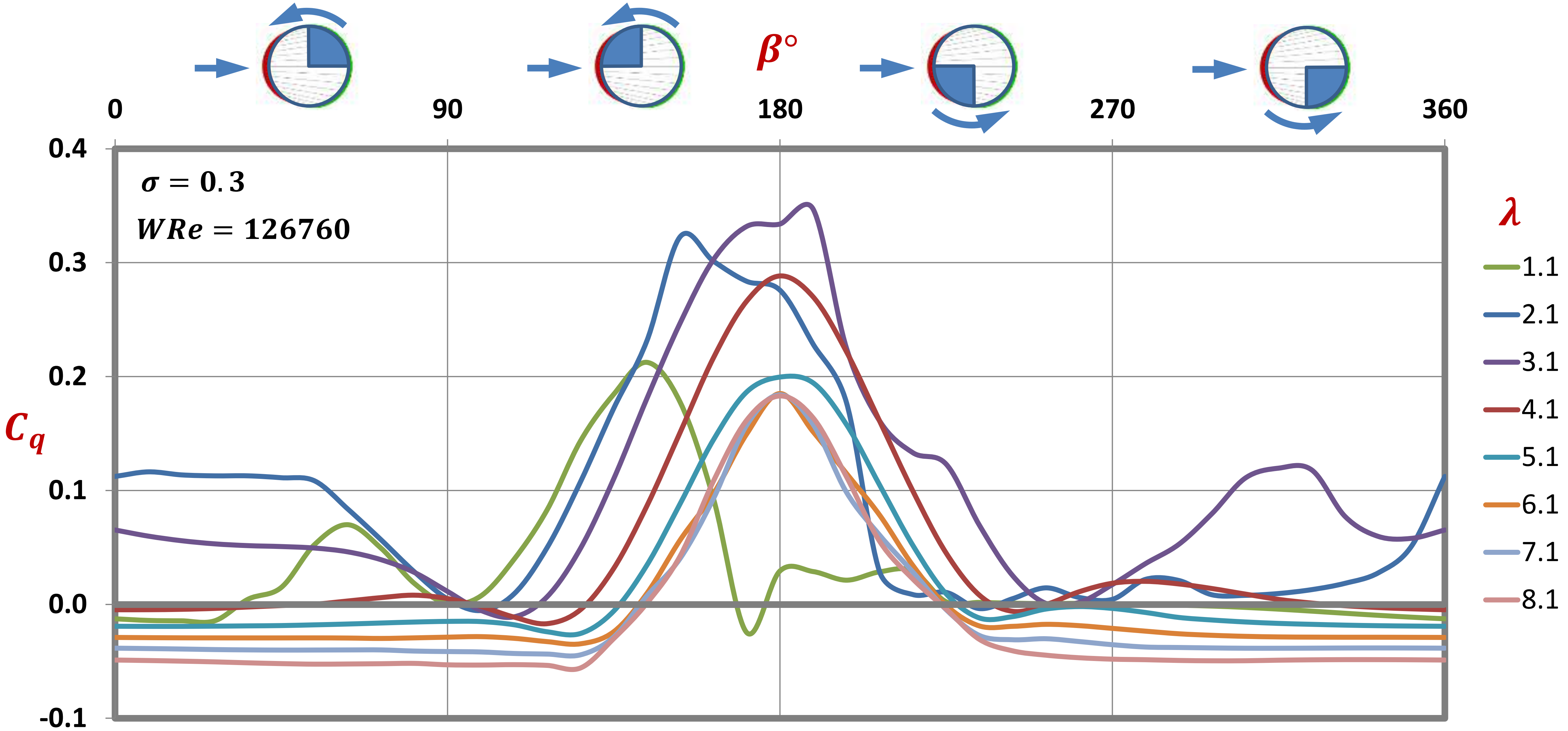
$\vartheta°$	$\beta°$	V_u/V_∞	$\beta°$	V_d/V_∞
0	180.0	0.821	0.0	0.463
10	172.8	0.824	12.8	0.471
20	165.4	0.832	25.4	0.495
30	157.8	0.845	37.8	0.535
40	149.9	0.863	49.9	0.589
50	141.6	0.885	61.6	0.655
60	132.9	0.911	72.9	0.732
70	123.8	0.939	83.8	0.816
80	114.3	0.969	94.3	0.907
90	104.4	1.000	104.4	1.000

after Sharpe & Read (1982)

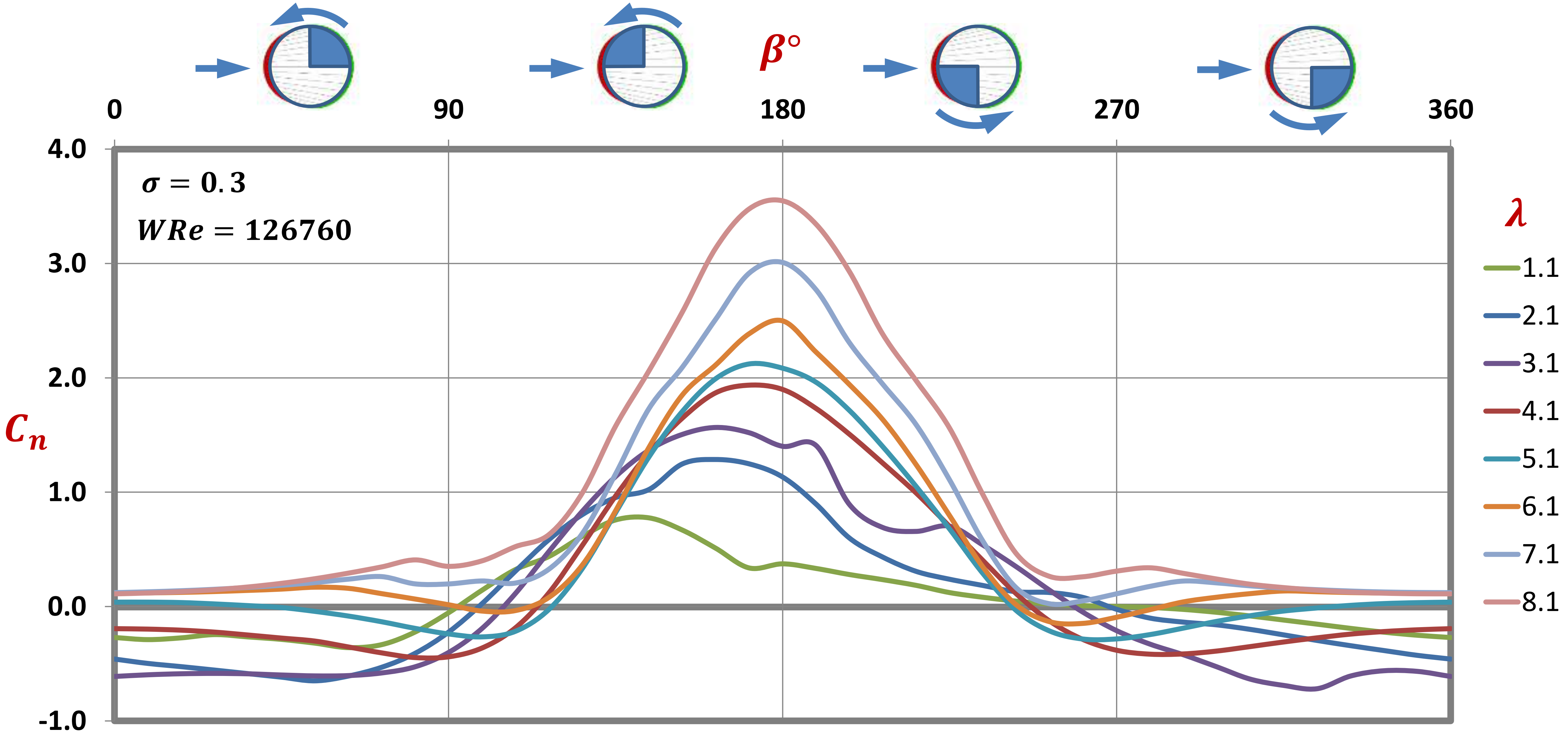
Flow Field Through Turbine $k = 0.358$



H-VAWT Characteristics: α° vs β°



H-VAWT Characteristics: $C_q vs\ \beta°$



H-VAWT Characteristics: $C_n vs\ \beta°$

How do the different VAWTs compare ?

GEOMETRY VARIATIONS

- The derivations presented so far assume an **H-type** VAWT with straight blades that are parallel to the axis of rotation

- The **Φ-type** (Troposkien Darrieus) and **V-type** VAWTs have blades with segments that are inclined to the vertical axis

- The **helical** (Gorlov) VAWT have blades that are inclined to the horizontal plane

- These geometry variations *increase* the effective area of the blade in the streamtube but *modify* the relative wind vectors and orientation of the aerofoil forces

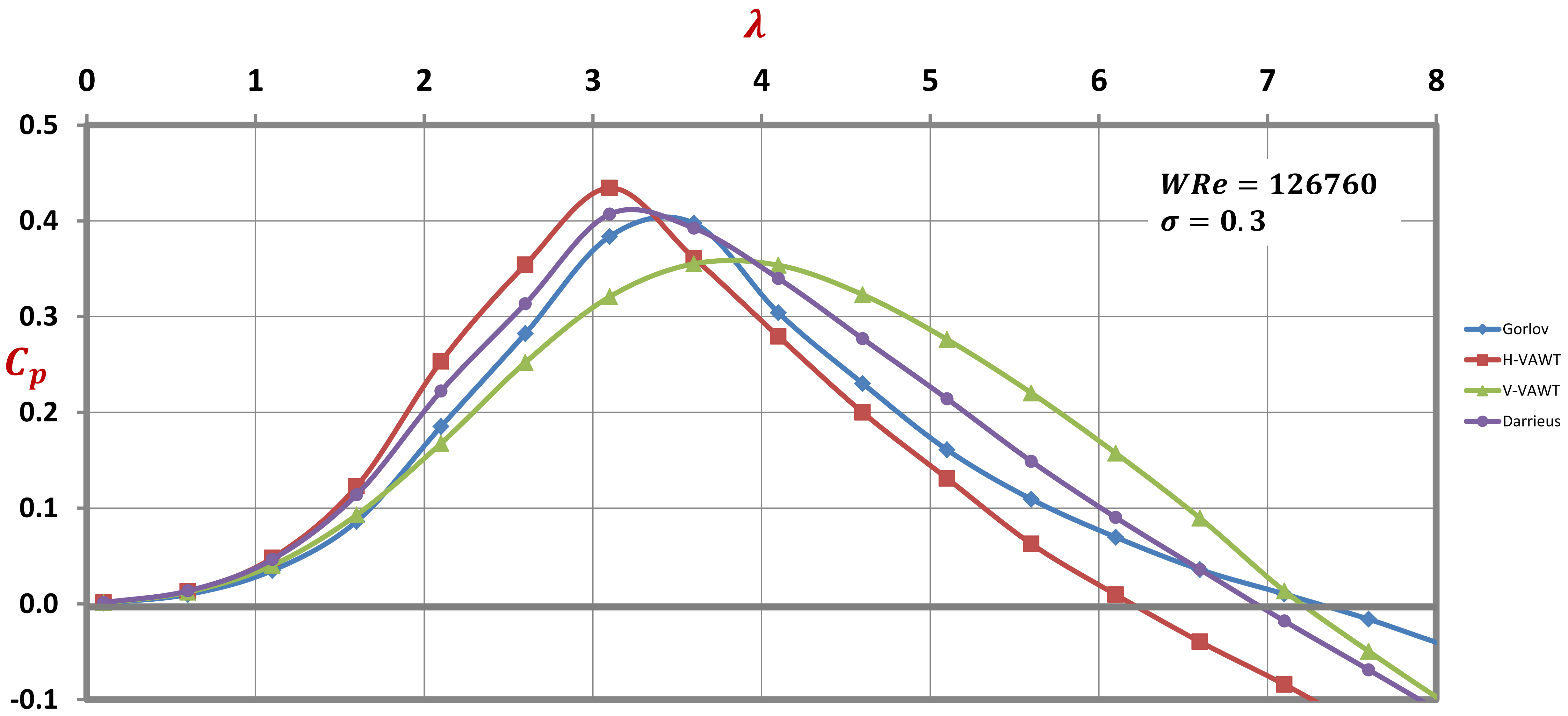
VAWT Geometry Variations

- The following studies are based upon the rotor geometry of a typical **helical** VAWT with $N = 3$ and $\sigma = 0.3$ operating in a constant windspeed of $V_\infty = 12\ m/s$

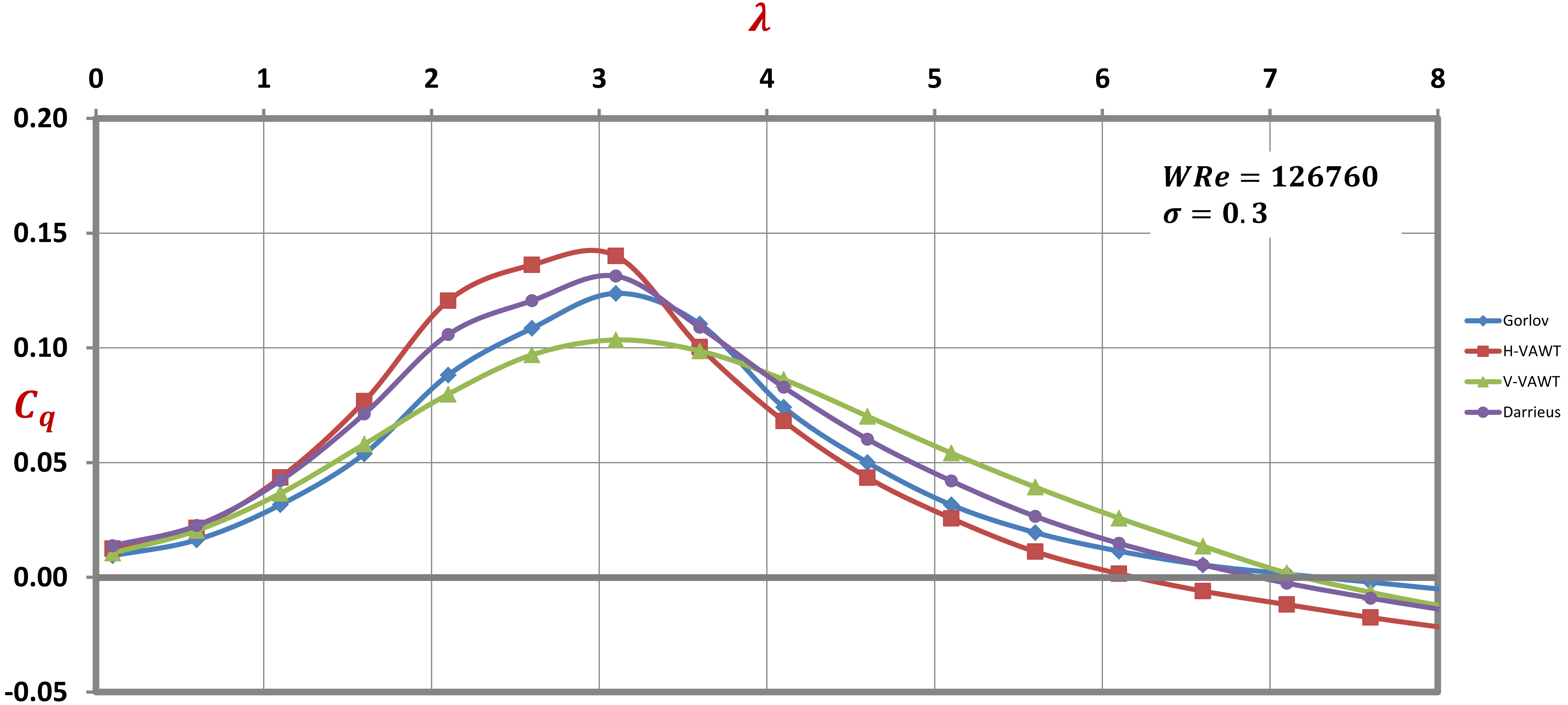
$V_\infty = 12\ m/s$	helical	H-type	V-type	Φ-type
Height (mm)	5300	5300	1500	3820
Diameter (mm)	3000	3000	3000	3000
Swept Area (m^2)	15.9	15.9	2.24	8.0
Chord (mm)	200	[illegible]	[illegible]	200
Blade Span (mm)	6161	[illegible]	[illegible]	5017
Angle $\psi°$	30.7°	-	-	-
Angle $\phi°$	-	-	45°	0° - 57°
Airfoil Section	NACA 0018			

$\cos^2\psi = 0.74$

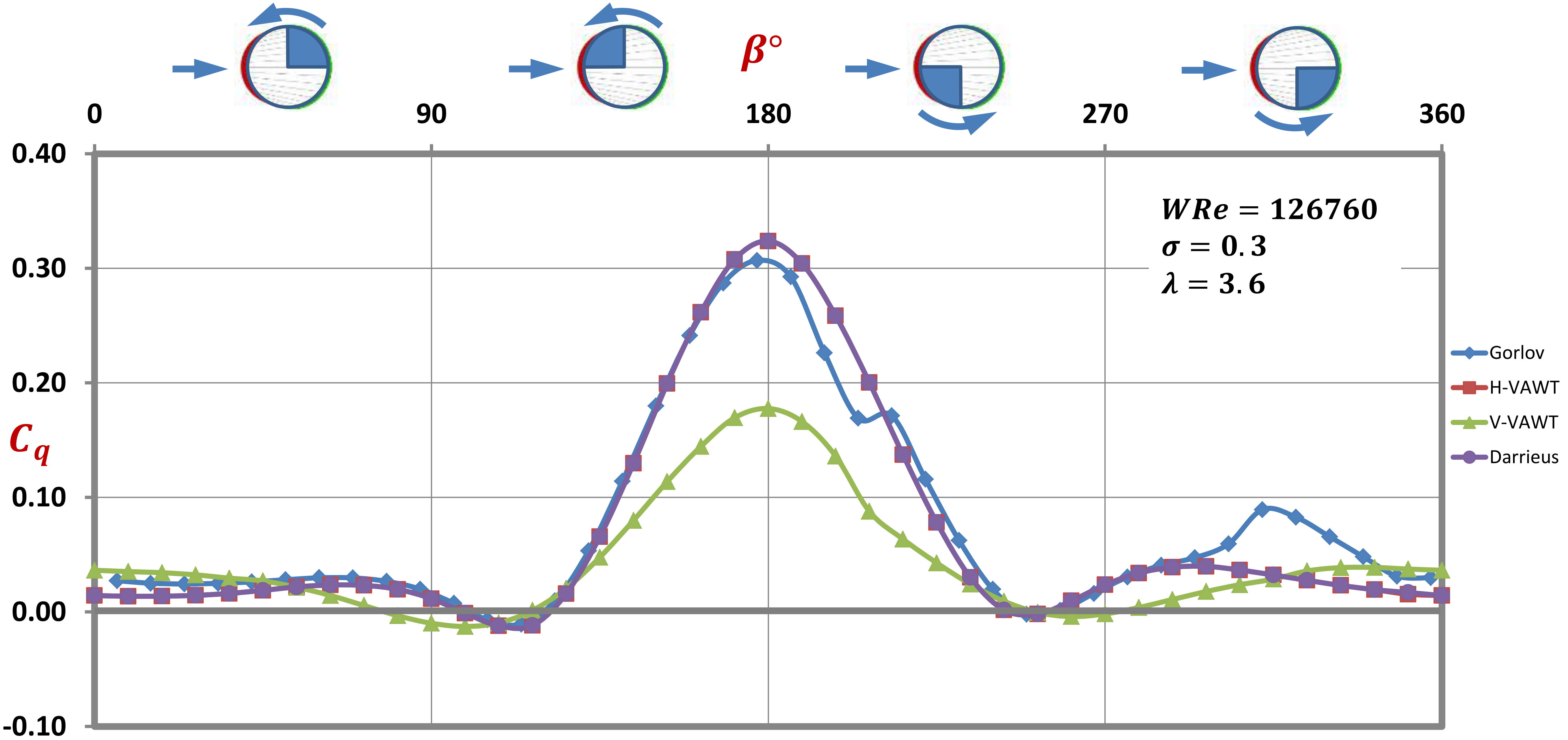
Trade Studies of VAWT Variations



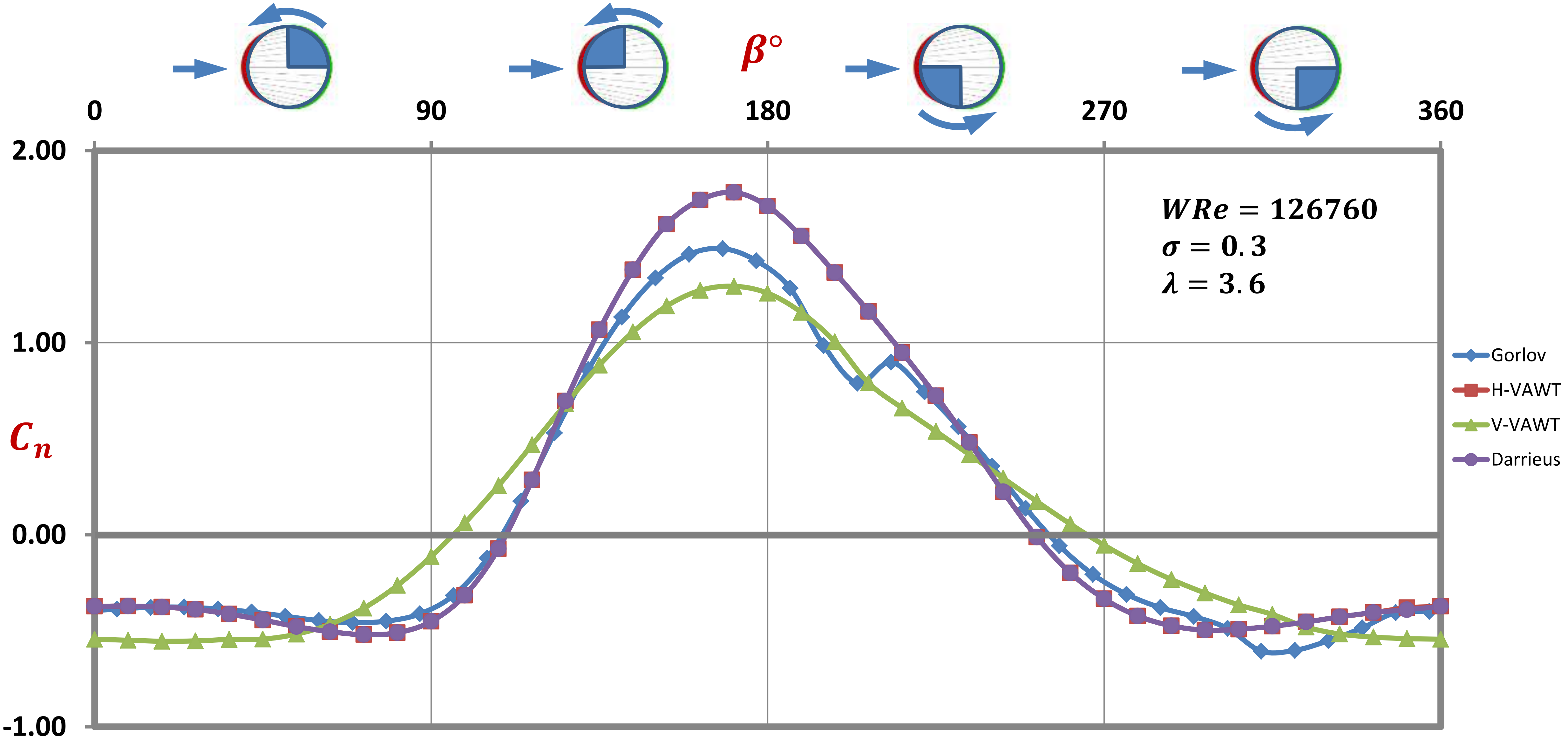
Trade Studies: $C_p vs\ \lambda$



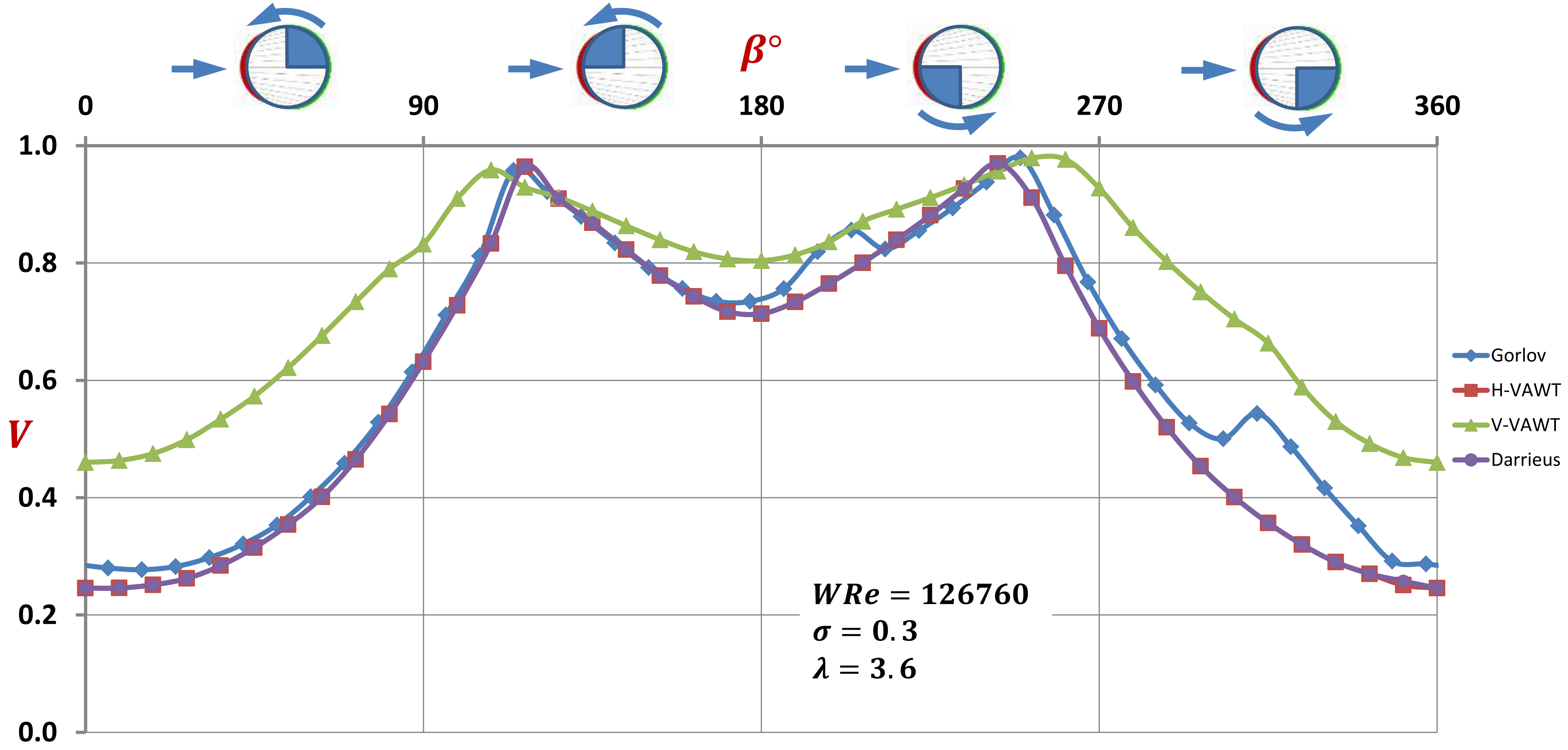
Trade Studies: $C_q vs\ \lambda$



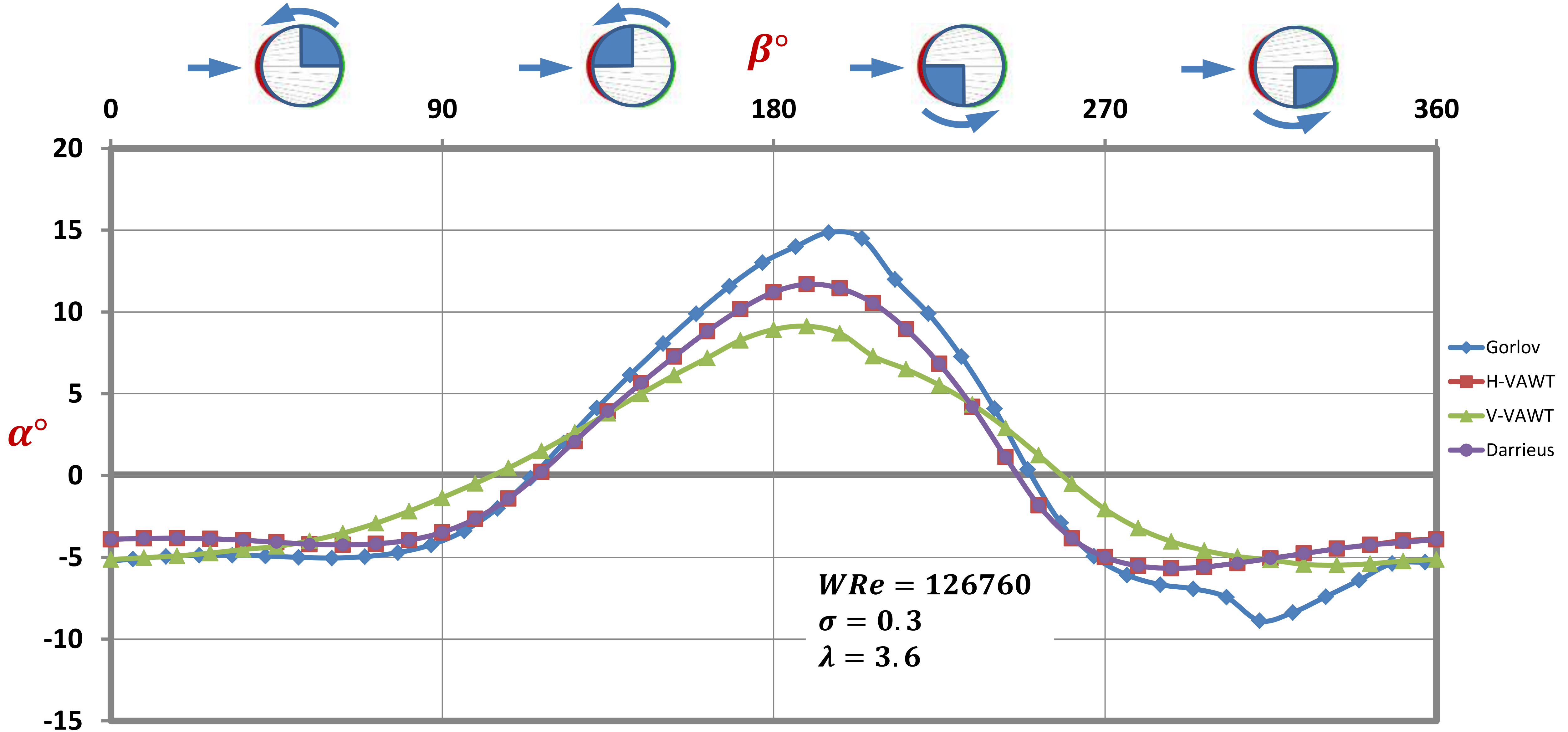
Trade Studies: $C_q\, vs\ \beta^\circ$ at Tip Radius



Trade Studies: $C_n vs\ \beta°$ at Tip Radius

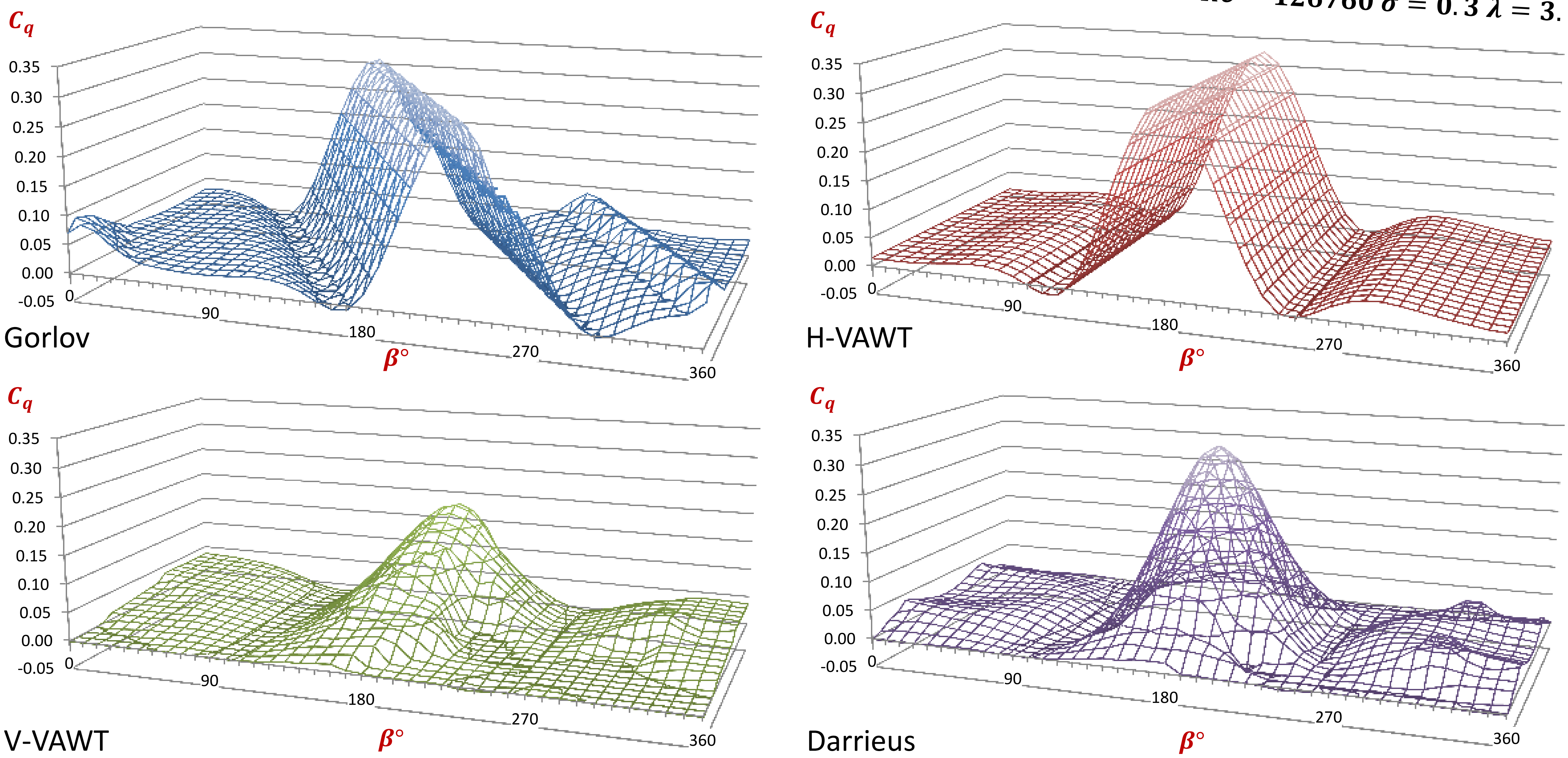


Trade Studies: V vs $\beta°$ at Tip Radius

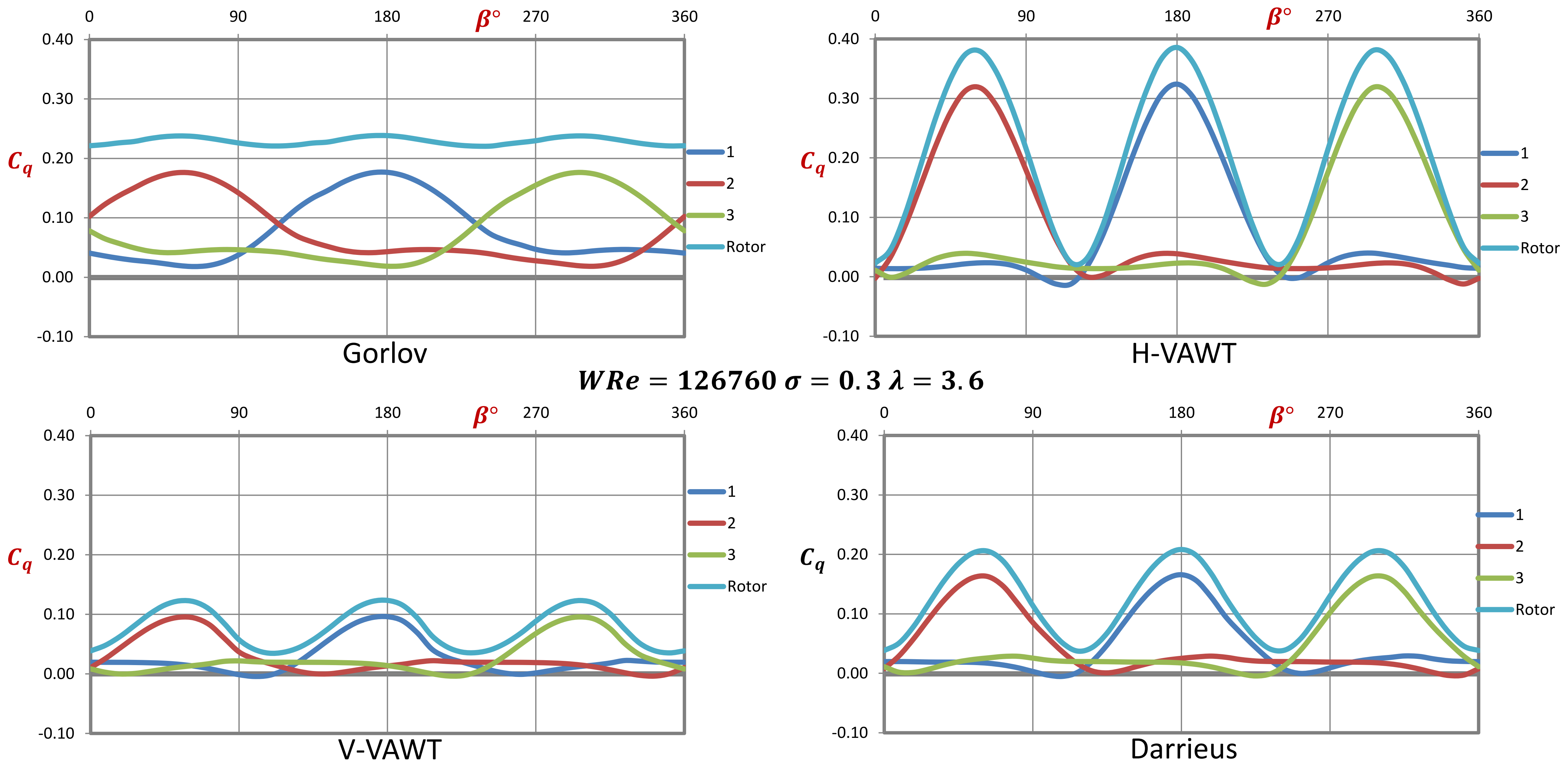


Trade Studies: $\alpha°$ vs $\beta°$ at Tip Radius

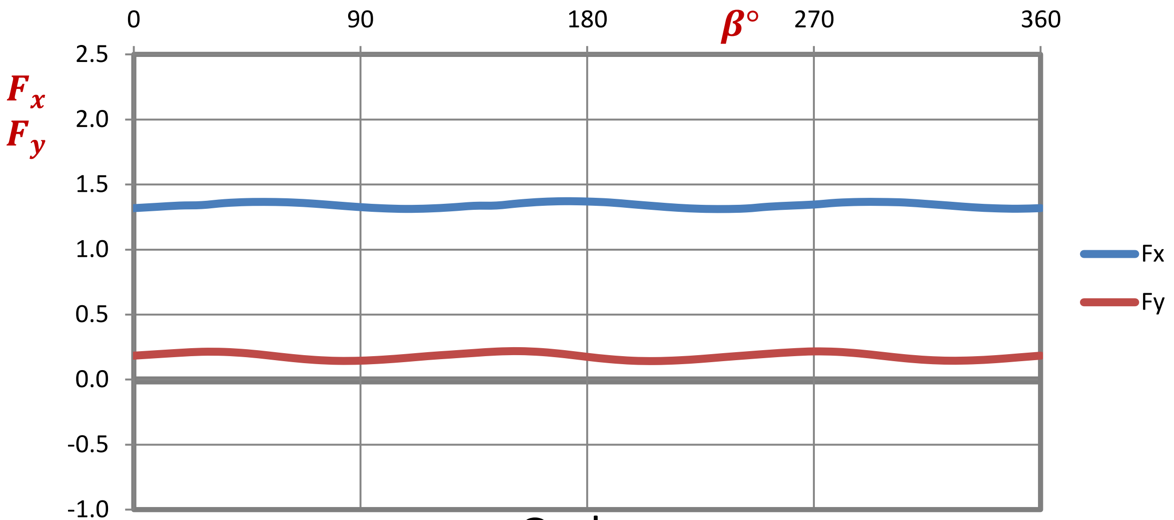
$WRe = 126760\ \sigma = 0.3\ \lambda = 3.6$



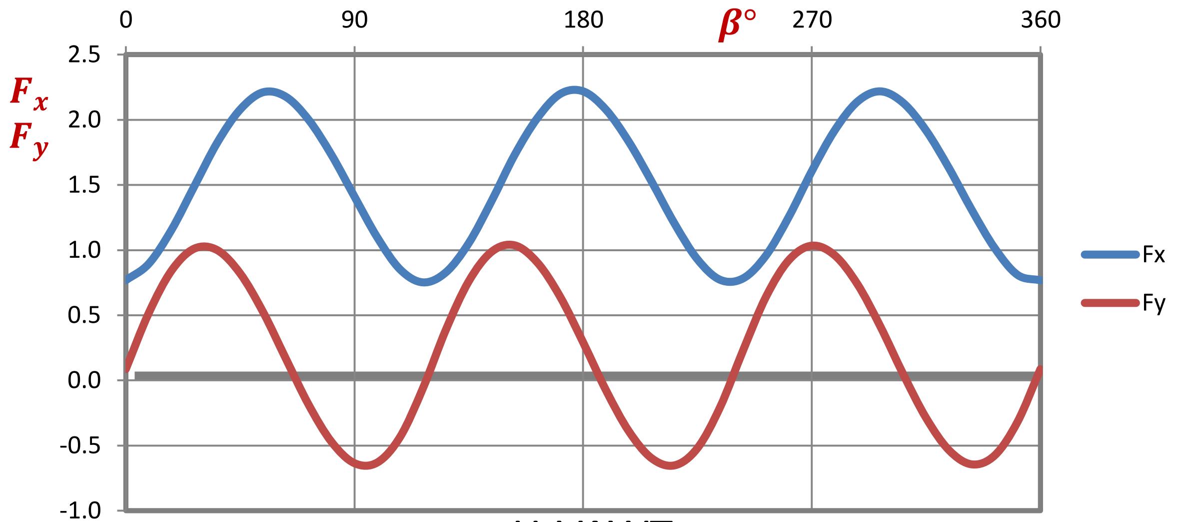
Spanwise Variation of $C_q vs\ \beta°$ at $\lambda = 3.6$



Blade Variation of $C_q vs\ \beta°$ at $\lambda = 3.6$

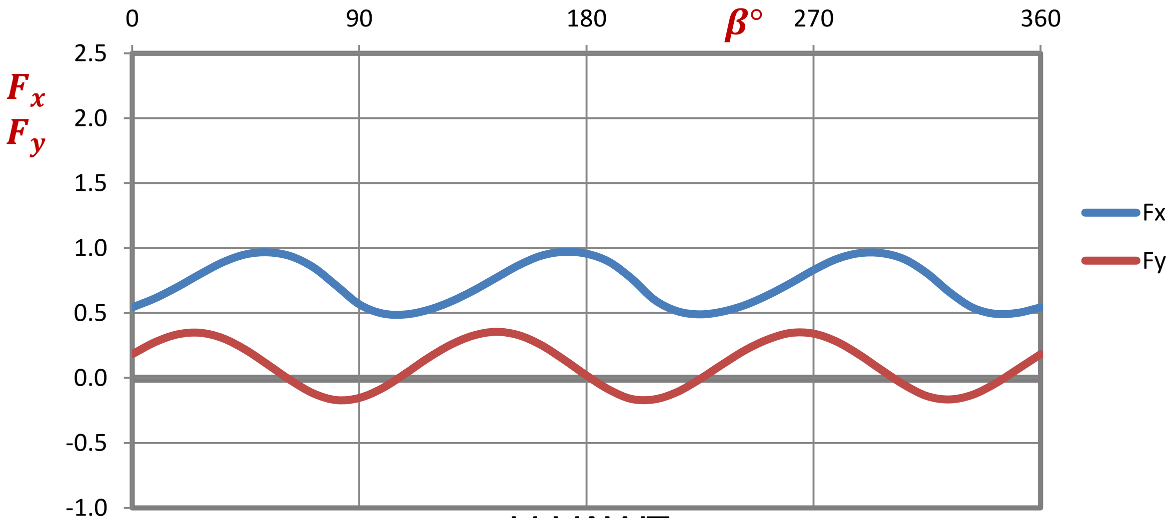


Gorlov

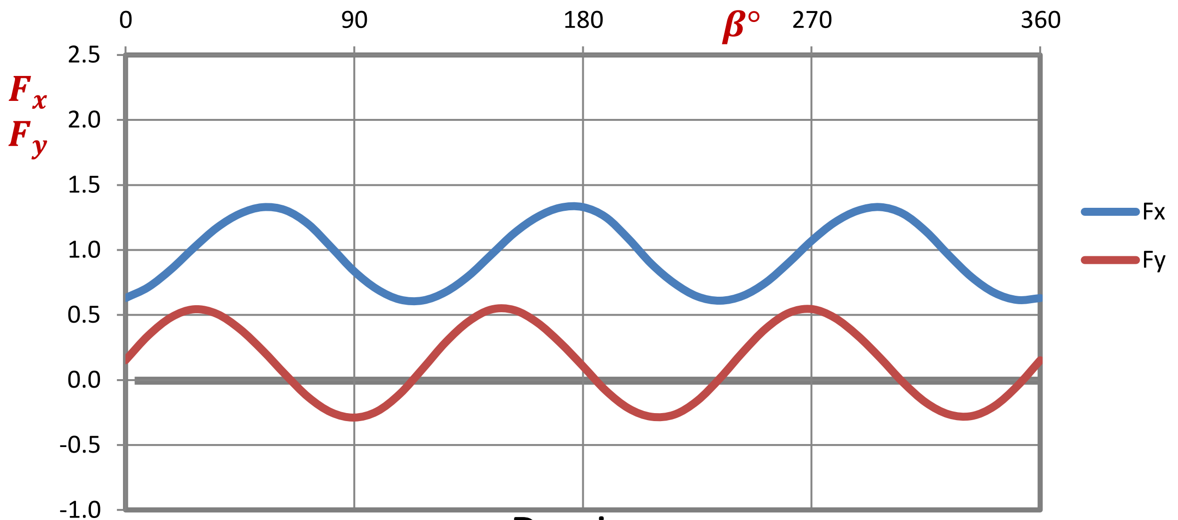


H-VAWT

$$\boldsymbol{WRe = 126760\ \sigma = 0.3\ \lambda = 3.6}$$



V-VAWT



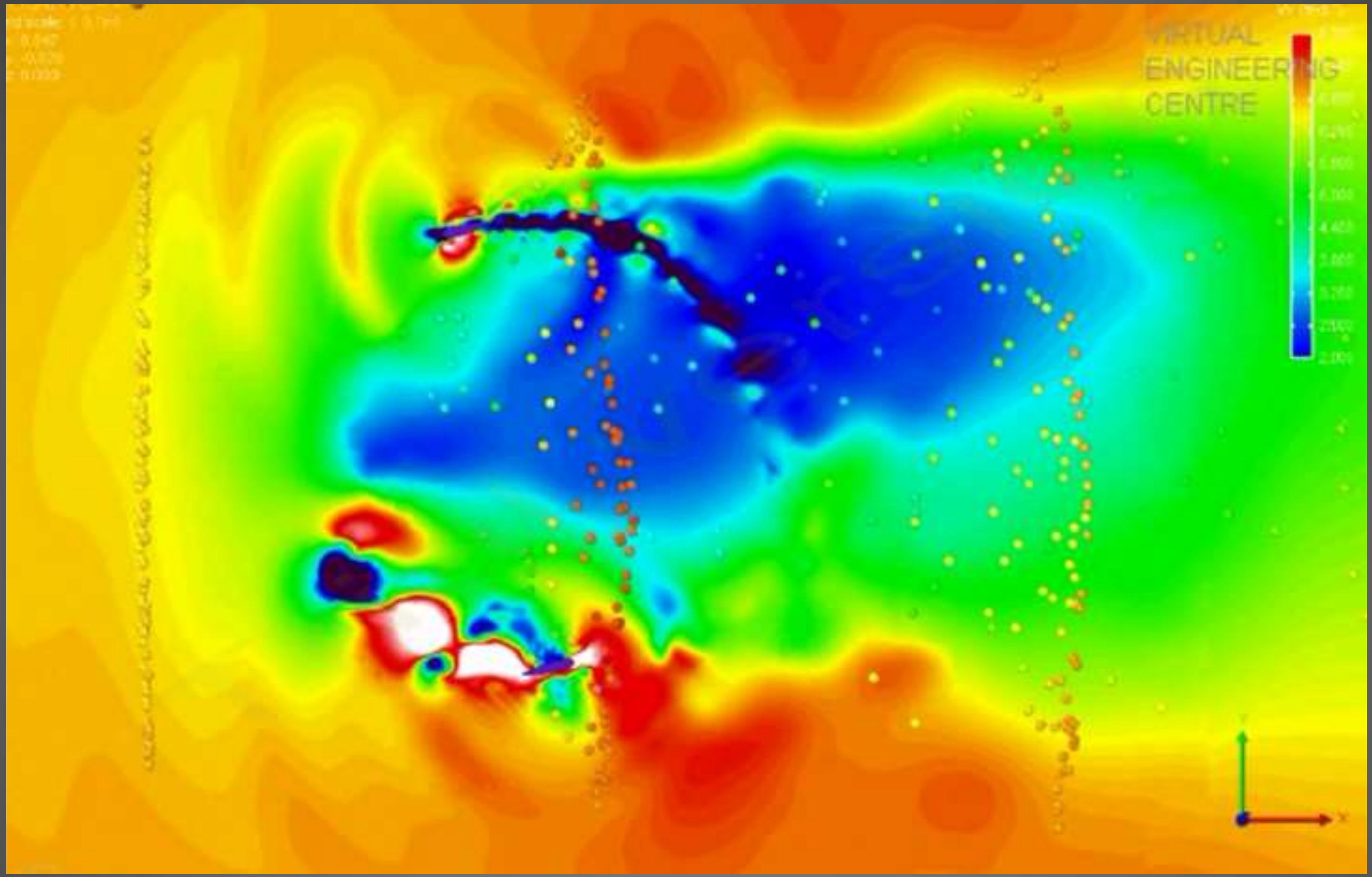
Darrieus

Tower Forces $F_x vs\ \beta°$ and $F_y vs\ \beta°$ at $\lambda = 3.6$

- The numerical results reflect the general observations made about how VAWT geometry influences aerodynamic performance

- The advantage of the helical VAWT is its favourable cyclic loading characteristic, which is offset by a small reduction in performance efficiency

Observations



AERODYNAMIC PREDICTIONS

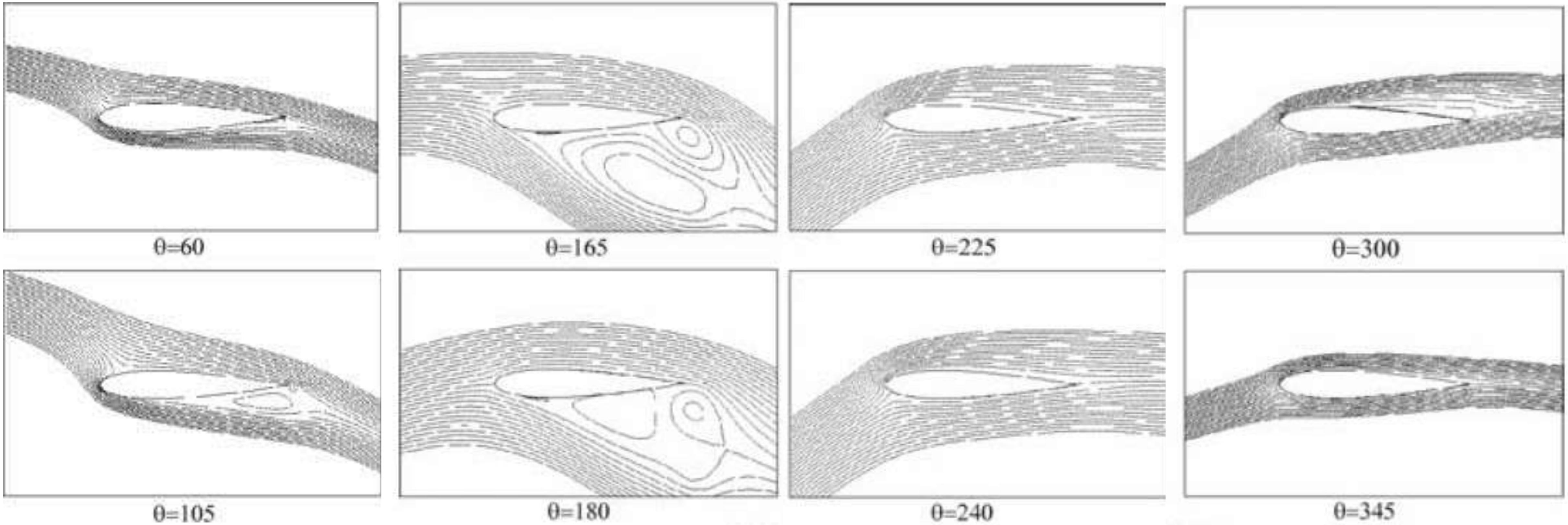
Whilst the multiple streamtube theory is useful for VAWT trade studies, it is limited by:

- Quality of available aerofoil data
- Models of Dynamic Stall
- Local blade geometry effects
- Theory breaking down with high solidity rotors (blockage)

Limitations of Streamtube Theory

Does CFD offer any substantial new insights into turbine behaviour ?

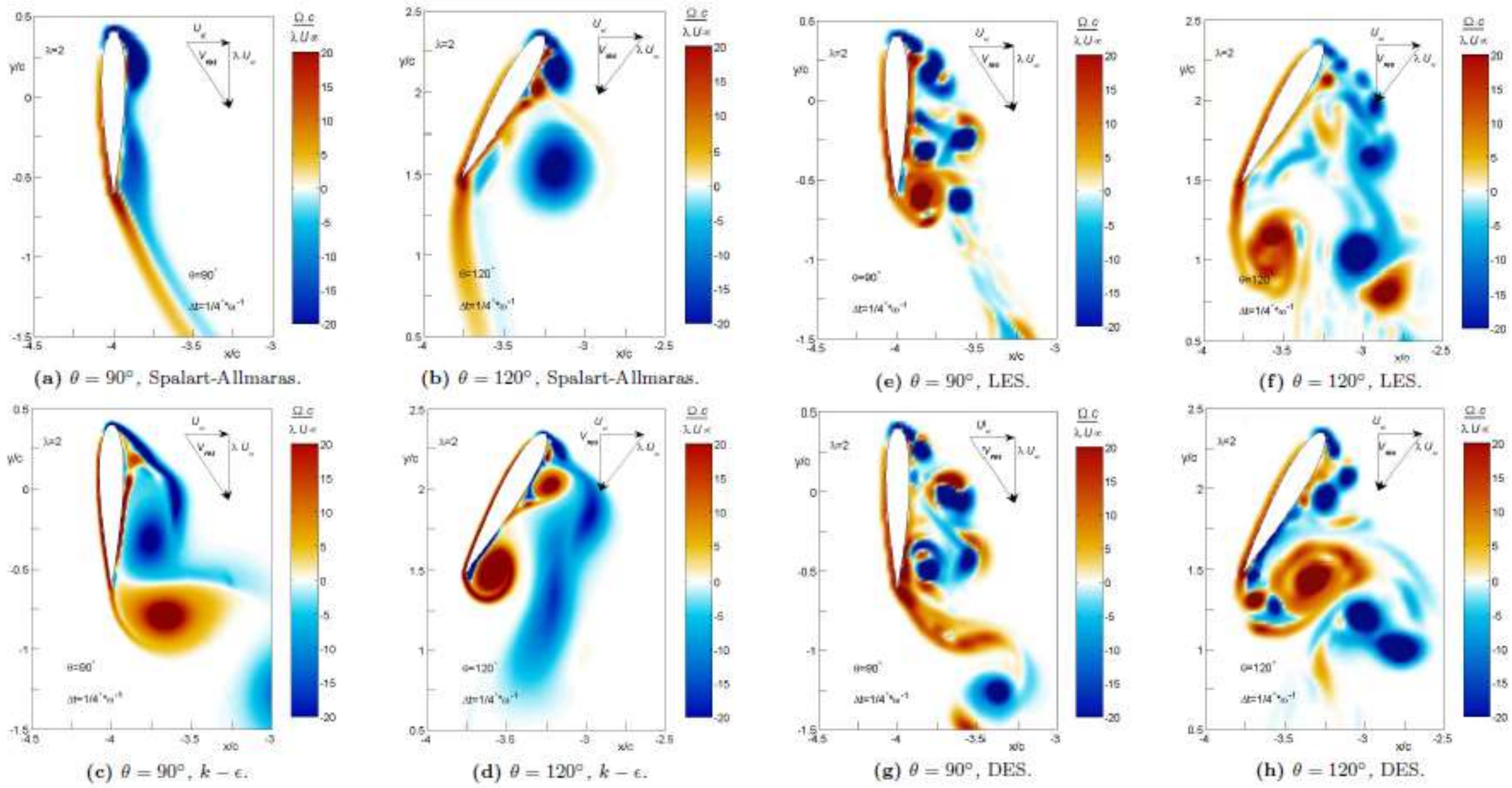
Numerical Simulation of Dynamic Stall



Streamlines

$\Psi = \psi_b \pm (0.03) \cdot n \quad$ *with n=0 to 12*

Paraschivoiu, I., Saeed, F. & Desobry, V. (2002)

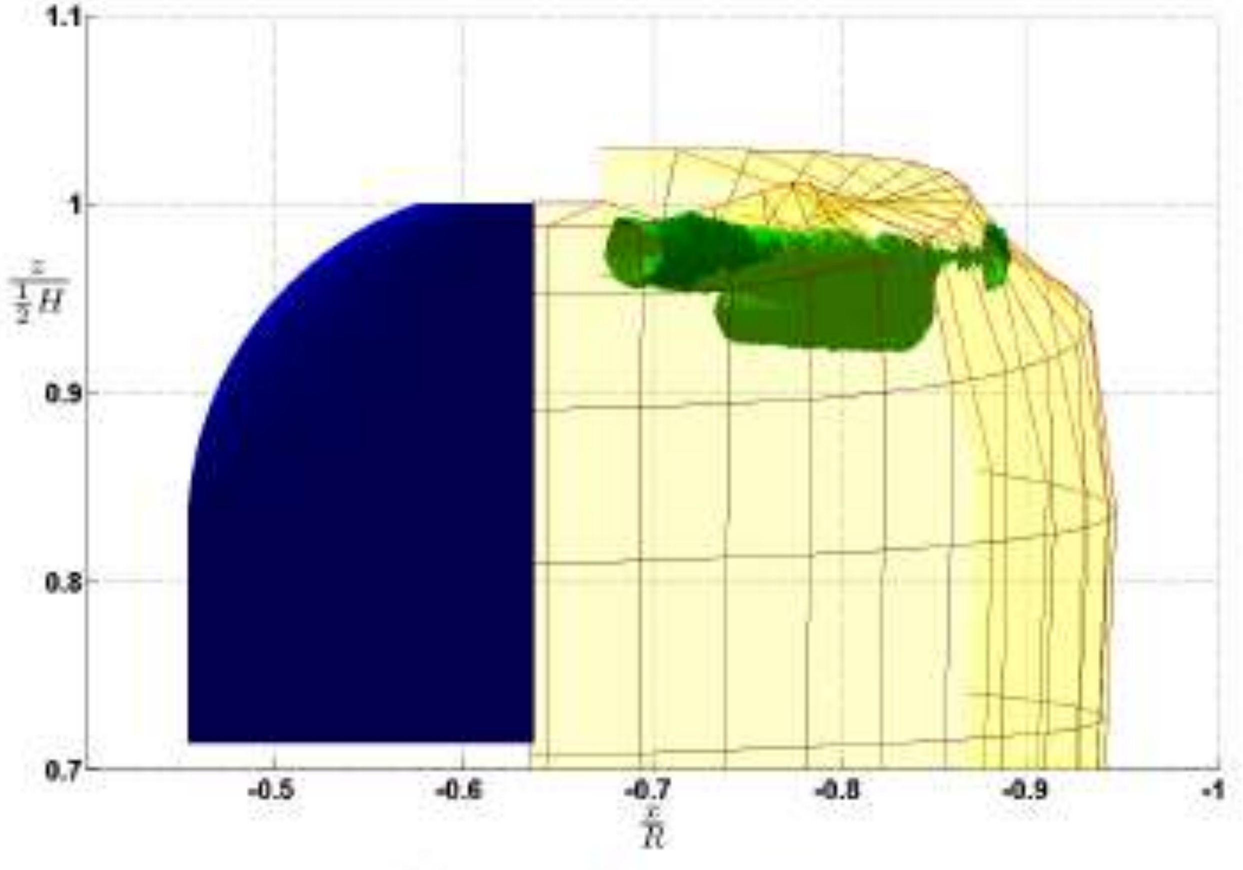


(a) $\theta = 90°$, Spalart-Allmaras. (b) $\theta = 120°$, Spalart-Allmaras. (e) $\theta = 90°$, LES. (f) $\theta = 120°$, LES.

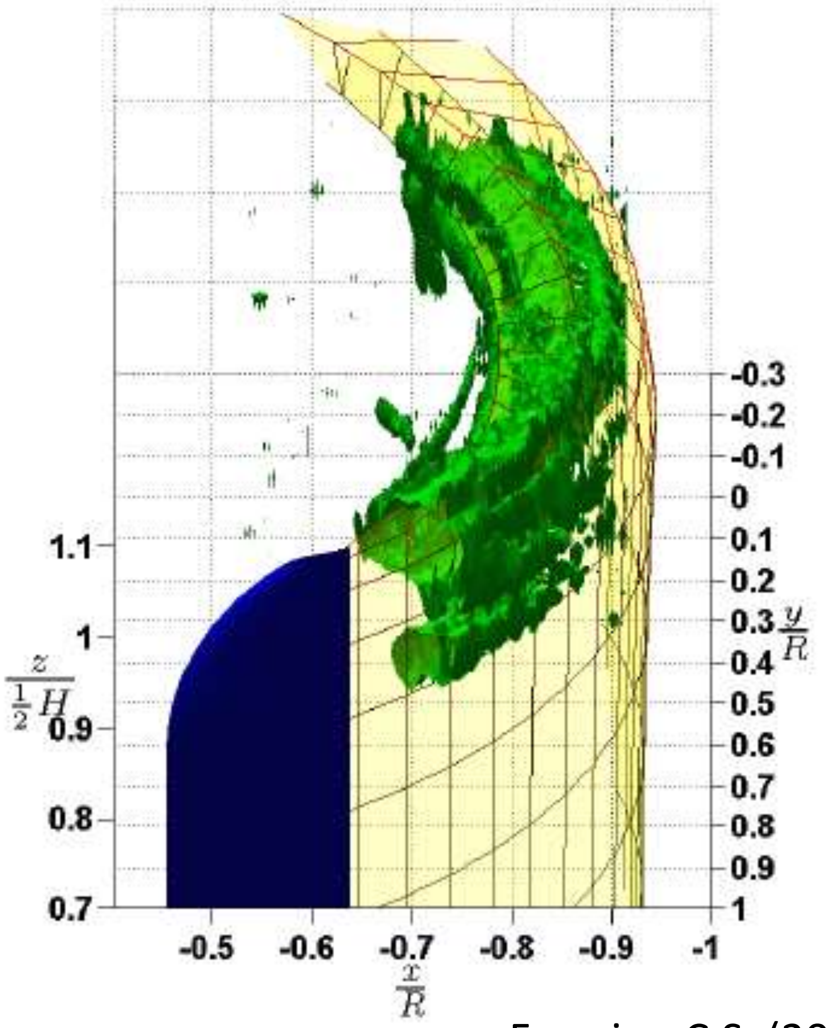
(c) $\theta = 90°$, $k-\epsilon$. (d) $\theta = 120°$, $k-\epsilon$. (g) $\theta = 90°$, DES. (h) $\theta = 120°$, DES.

Ferreira, C.S. (2009)

2D CFD Simulation of Dynamic Stall

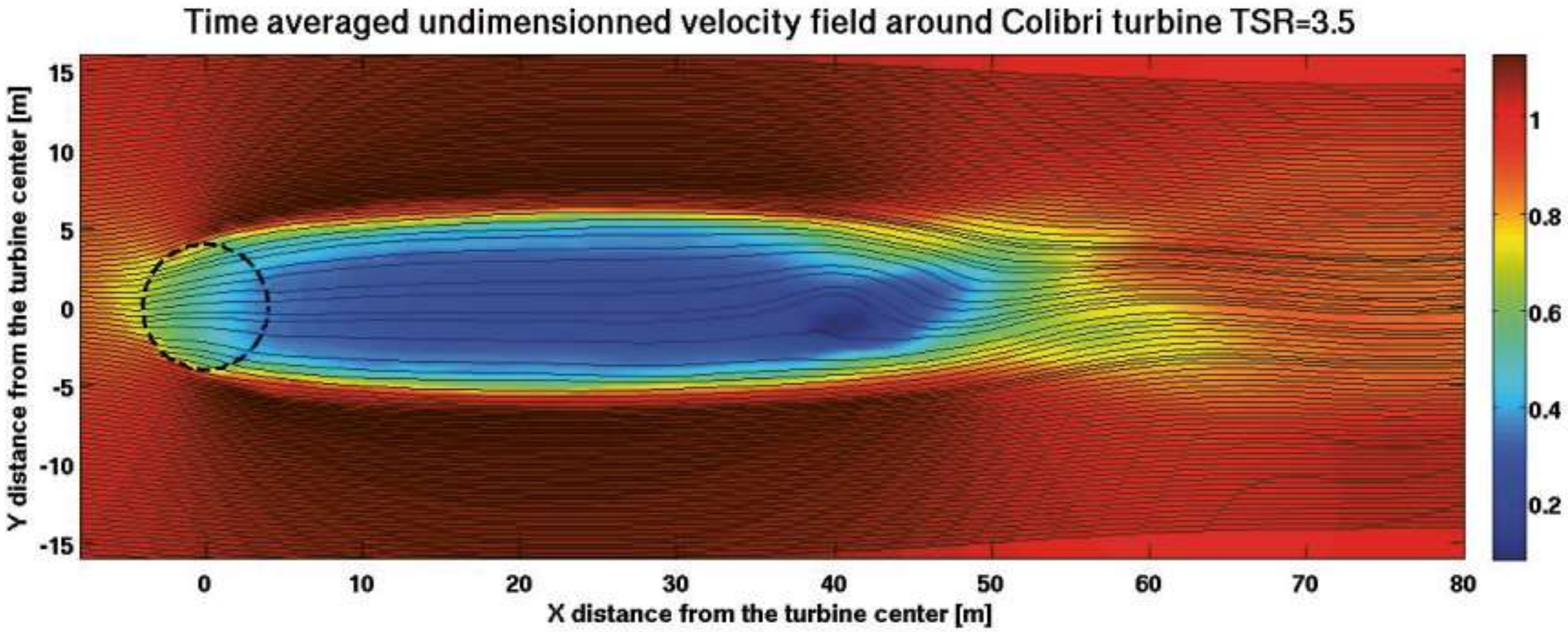


(c) *View c), xz plane.*



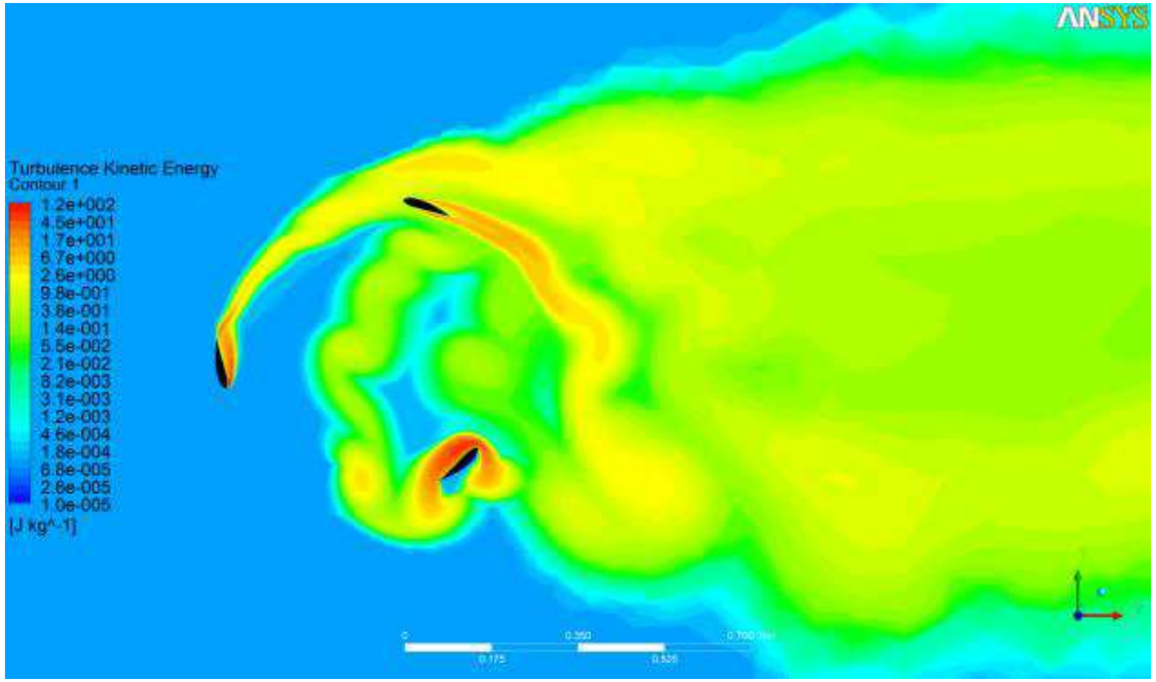
Ferreira, C.S. (2009)

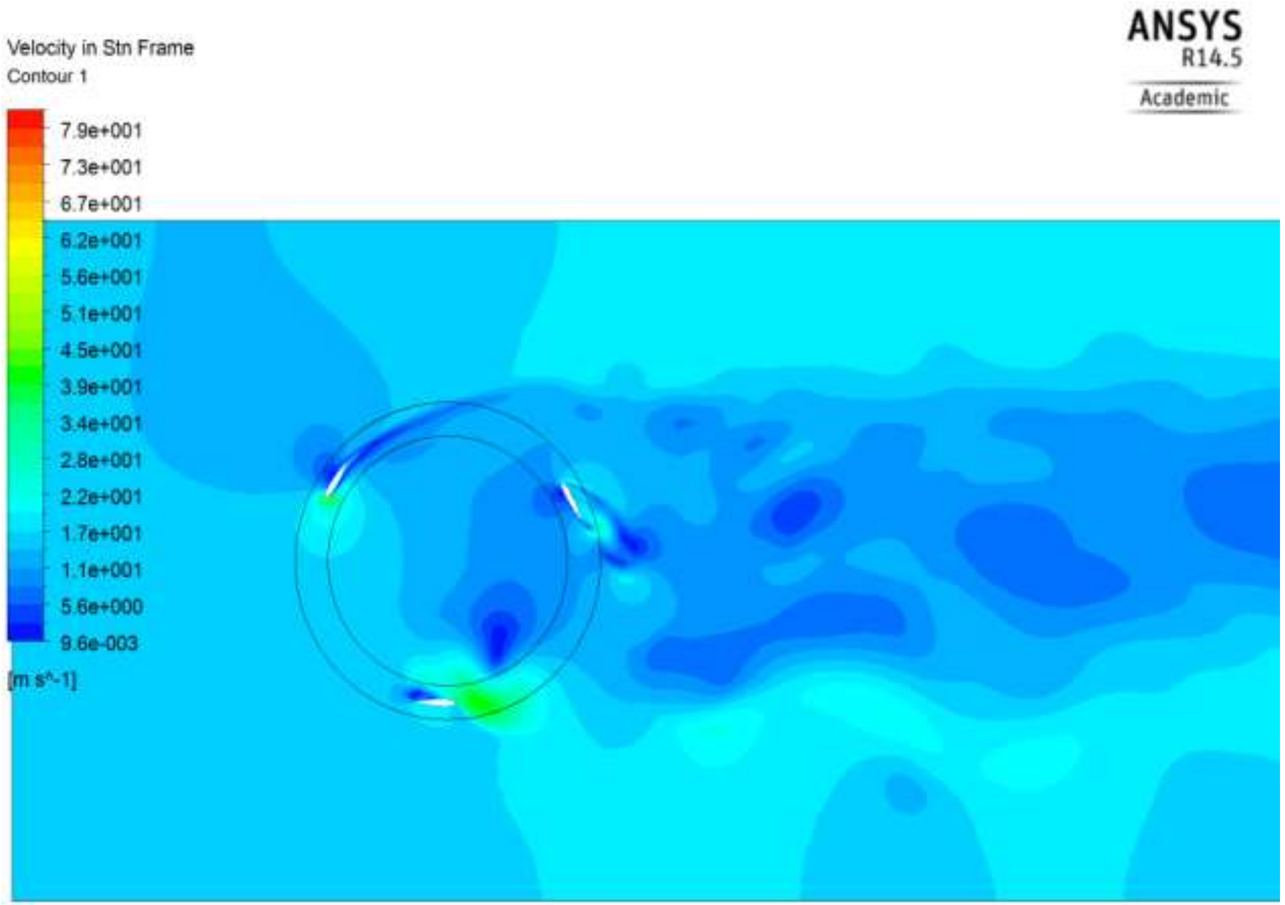
3D CFD Tip Effects – Iso-Vorticity Surfaces



Deglaire, P. (2010)

2D CFD Velocity Field





Lanzafame, R., Mauro, S. & Messina, M. (2013)

Turbulent KE and Relative Velocity

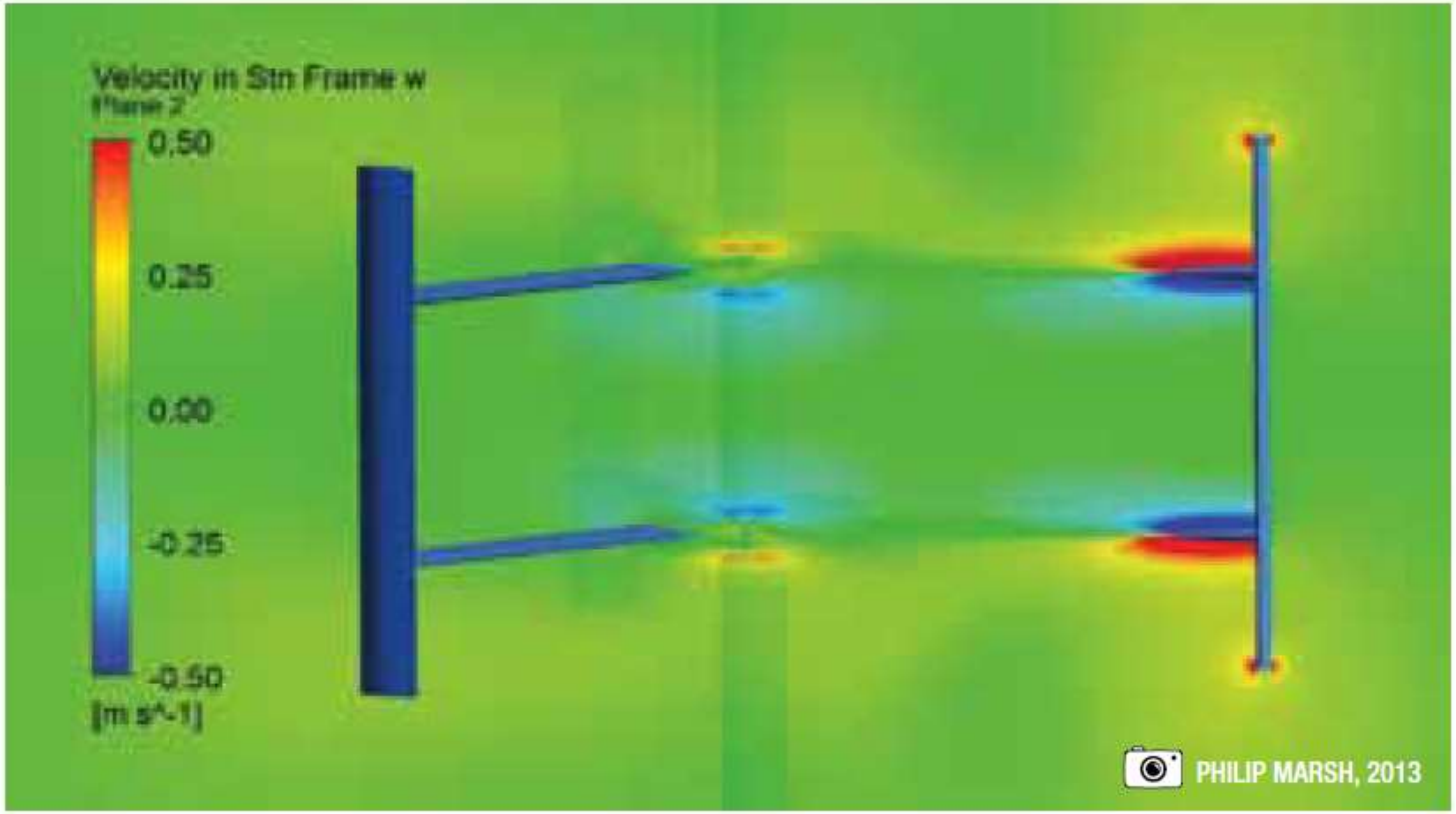
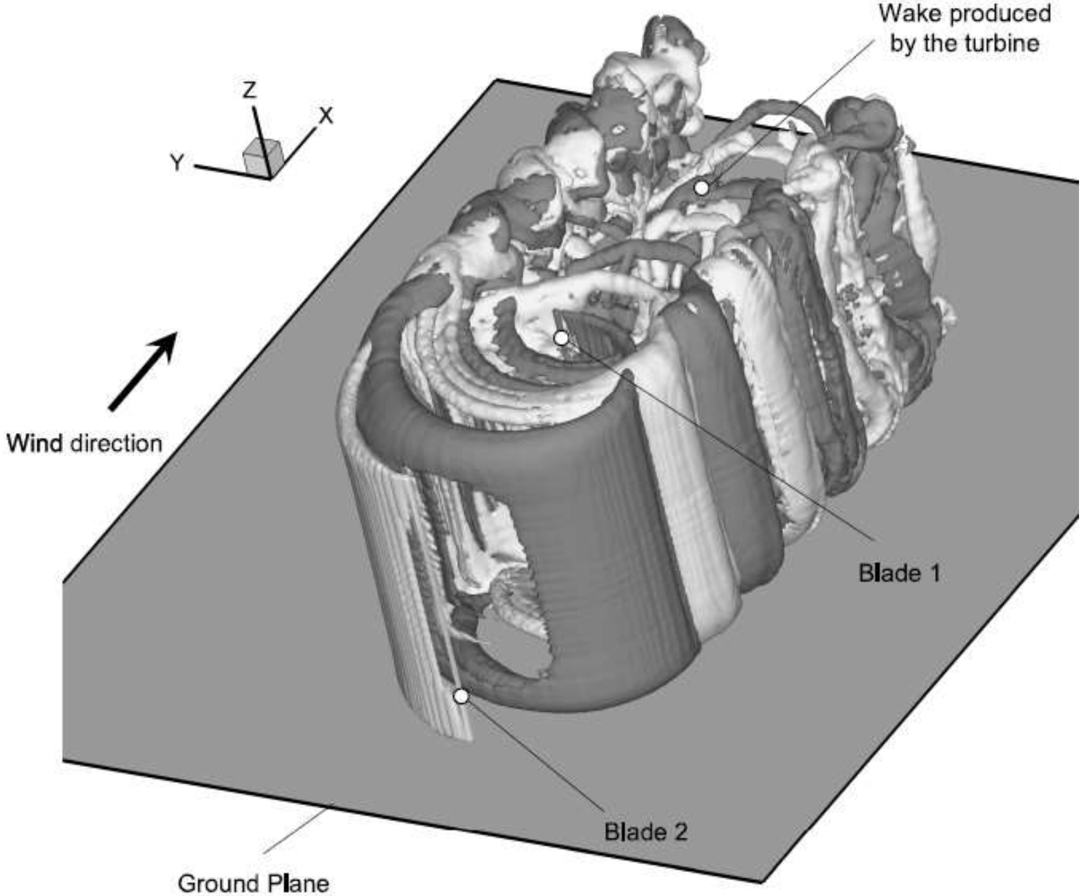


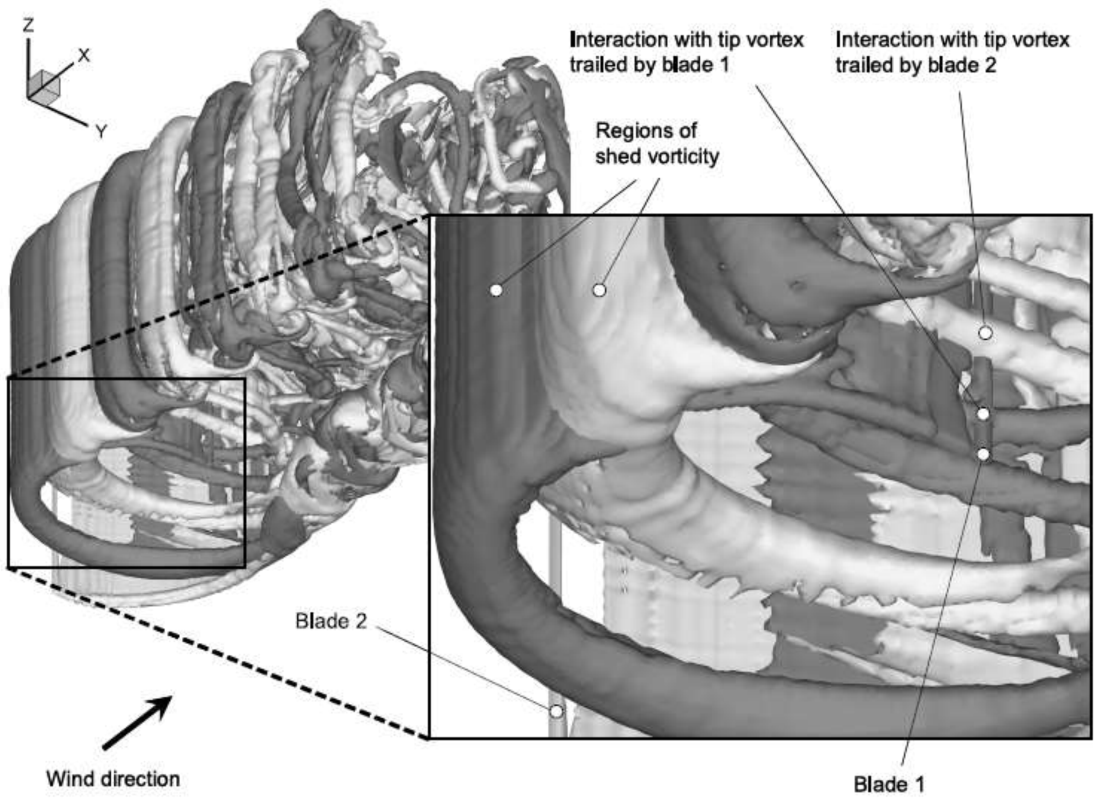
Figure 10 (left): Flow velocity $\overline{w}$ (m/s) for the 3D Computational Fluid Dynamics model with appendages at λ of 2.
Figure 11 (right): Vortex visualization of 3D Computational Fluid Dynamics model with appendages. Helicity of 6 m/s^2 at λ of 2.

Marsh, P., Ranmuthugala, D., Penesis, I. & Thomas, G.(2013)

Flow Velocity & Vortex Shedding



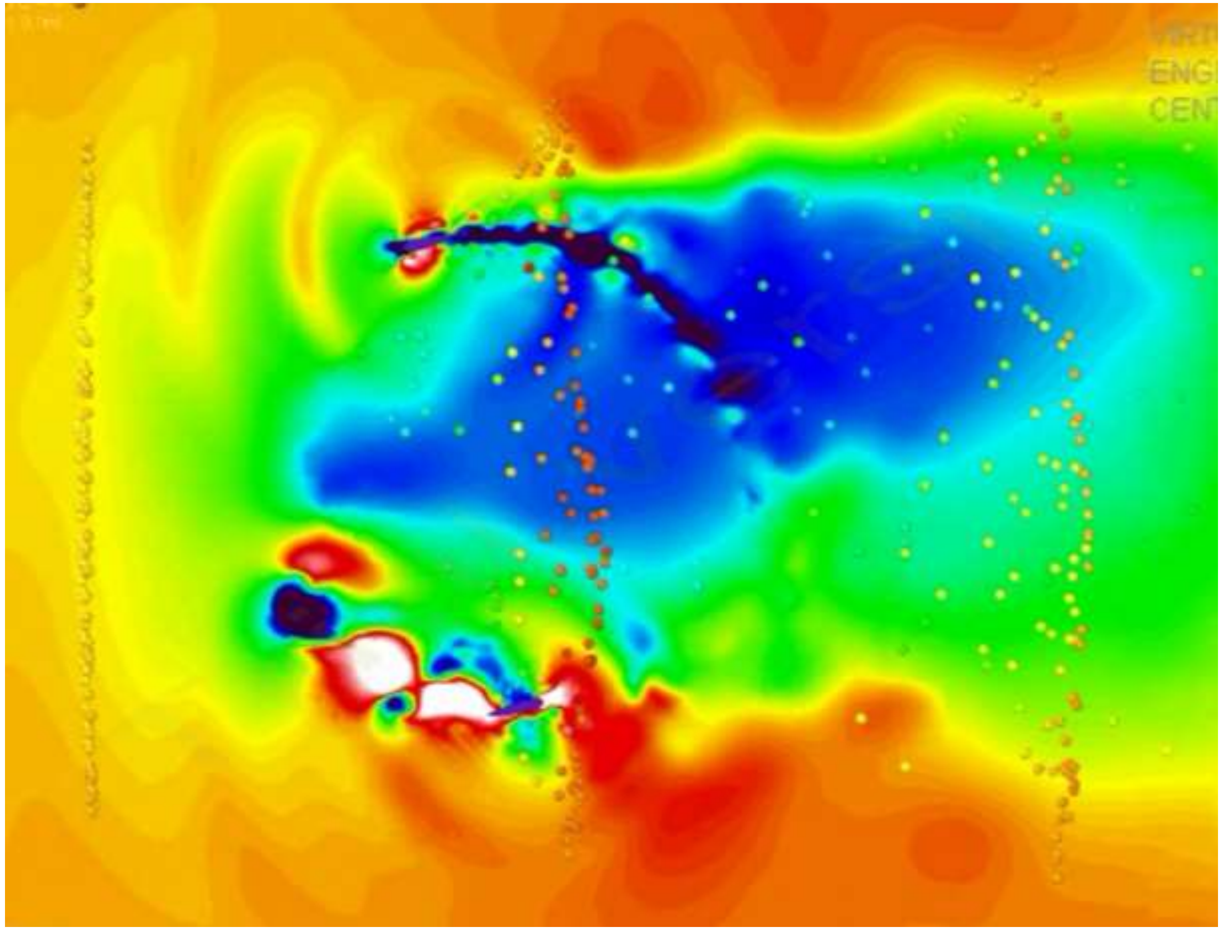
(a) *Propagating wake produced by the turbine.*

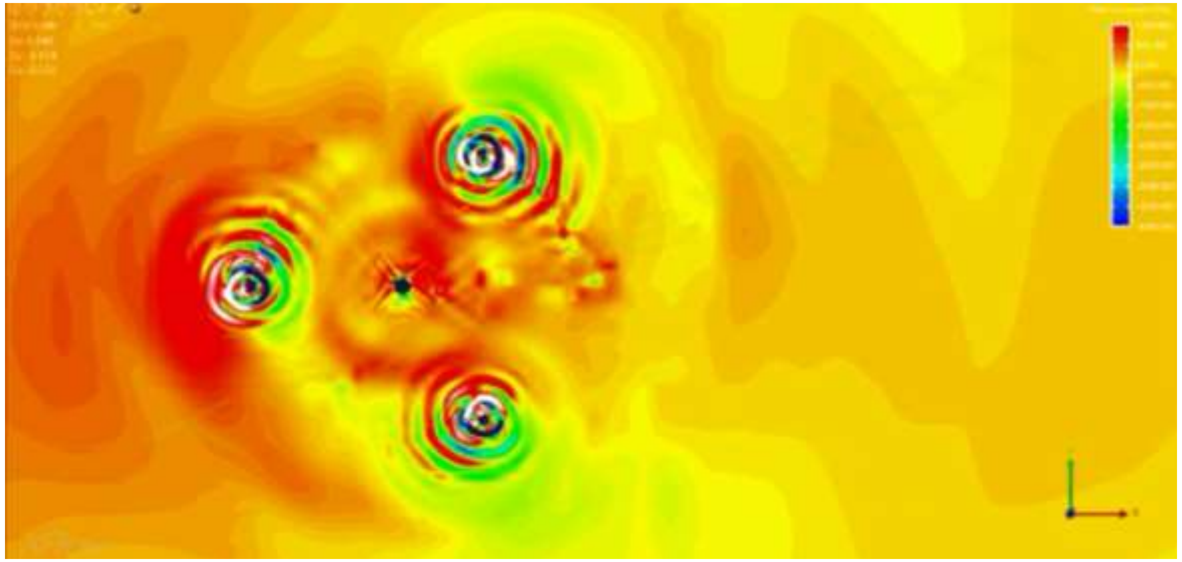


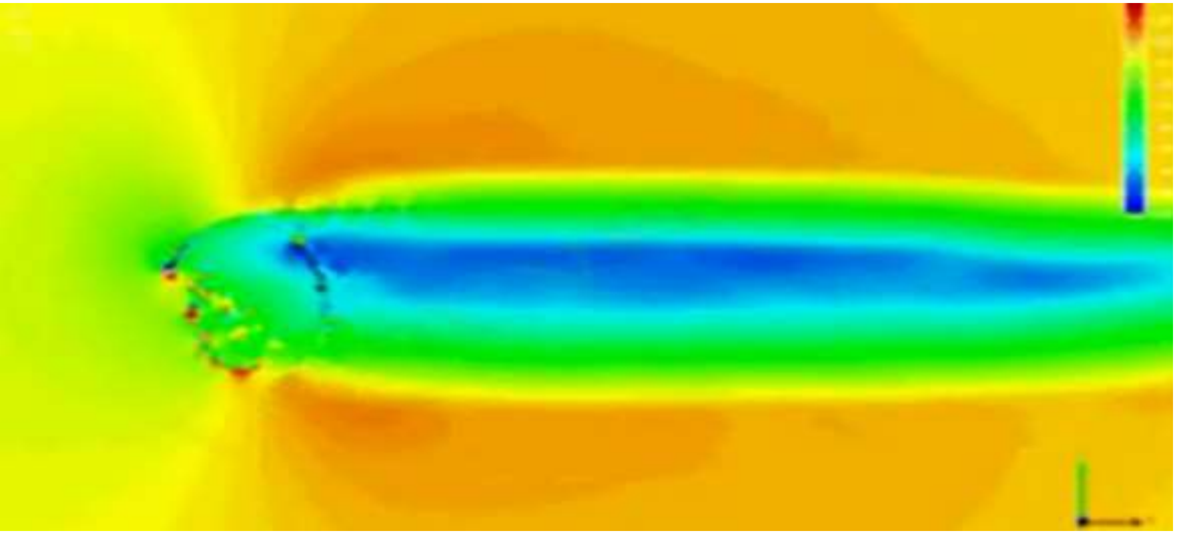
(b) *Interaction between blade 1 and its own trailed vortex and the tip vortex trailed by blade 2.*

Scheurich, F., Fletcher, T.M., & Brown, R.E.(2011)

VAWT Wakes







Meshless CFD Simulations - XFlow

- CFD offers substantial new insights into VAWT behaviour that are well beyond the capabilities of the multiple streamtube theory … but multiple streamtube theory remains a valuable tool for design configuration

- However, we sadly lack the data to validate numerical results from either approach

Observations

CONCLUDING REMARKS

- The **Vertical Axis Wind Turbine** is an under utilised wind energy technology

- The **Helical VAWT** should dispel concerns over long-term fatigue due to cyclic loading of the structure

- **CFD** tools are attractive options for dynamic/transient flows, moving bodies and complex body surfaces but the simplicity of the **multiple streamtube theory** makes it useful as a conceptual design tool

- The **challenges remain much the same** with a lack of field and experimental data for validation coupled with a **20+ year lag** in commercial development

Conclusions

Thank You!

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References

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